LMSC-D153408

SPACE TUG ECONOMIC ANALYSIS STUDY

NAS 8-27709

FINAL REPORT
DR MA-04

VOLUME II: TUG CONCEPTS ANALYSIS

PART 1 – OVERALL APPROACH AND DATA GENERATION

Prepared for
National Aeronautics & Space Administration
George C. Marshall Space Flight Center

Lockheed Missiles & Space Company, Inc.
Sunnyvale, California
and
Mathematica Inc.
Princeton, New Jersey

LOCKHEED

NASA

MATHEMATICA, INC.

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FOREWORD

This report summarizes work accomplished under the Space Tug Economic Analysis Study on Contract NAS8-27709. This study was performed for the NASA Marshall Space Flight Center by Lockheed Missiles & Space Company, Inc. of Sunnyvale, California, and Mathematica, Inc. of Princeton, New Jersey. The period of technical performance was nine months, starting July 26, 1971.

The NASA Contracting Officer's Representatives for this program were Lieutenant Commander William C. Stilwell (USN) and Mr. Richard L. Klan. The study team was led by Mr. Charles V. Hopkins of Lockheed and Dr. Edward Greenblat of Mathematica. Task leaders on the Lockheed team were as follows:

John P. Skratt – Data Integration and Interpretation
William T. Eaton – Payload Data and Payload Effects Analysis
Richard T. Parmley – Tug Definition

Other key team members included:

Anthony G. Tuffo – Data Mechanization and Evaluation
Zoe A. Taulbee – Computer Programming
Jolanta B. Forsyth – Payload Costs and Benefits; Tug Cost Model
Kenneth J. Lush – Program Costing Logic

This report is organized as follows:

- Volume I – Executive Summary
- Volume II – Tug Concepts Analysis
  - Part 1: Overall Approach and Data Generation
  - Part 2: Economic Analysis
  - Appendix: Tug Design and Performance Data Base
- Volume III – Cost Estimates

Volume II contains detailed discussions of the methods used to perform this study, and of the major findings that have resulted. For convenience Volume II has been further divided into three parts. Part 1 discusses the overall study approach and documents principal Lockheed results in data generation and interpretation.

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CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Chapter 1
INTRODUCTION

Part 1 of Volume II establishes the overall approach used in the Space Tug Economic study, and then focuses on the specific procedures and results derived by Lockheed during the analytical effort. The specific organization of Volume II, Part 1 is described in the following paragraphs.

Chapter 2 is a summary of the Lockheed/Mathematica approach to the study, including the three principal tasks of building the data base, integrating and interpreting the data, and performing the economic analysis. The remaining chapters of Part 1 discuss the first two of these three steps; the economic analysis is treated in Part 2 of Volume II.

Chapter 3 presents details of the Tug and payload information that comprise the data base from which all subsequent analyses were derived. The first part of this chapter discusses the approach used in formulating the data base; the second part presents examples of design, performance, and cost information from the data base. For a complete presentation of data base information refer to the following documentation:

- Tug design and performance data – Volume II, Appendix
- Tug costs and payload costs and characteristics – Volume III

Chapter 4 discusses at length the techniques used by Lockheed in performing the data integration and interpretation task and important results from this task. Chapter 4 is divided into two major sections. The first presents details of the technical approach to data integration, including computer program flow diagrams. The second section presents results of the Lockheed data-interpretation effort, including Tug concept comparisons and sensitivity studies; this section also explains the driving factors underlying the variations in total program cost between Tug configurations and system variables.

SUMMARY OF APPROACH

Chapter 2

SUMMARY OF APPROACH

The overall approach used by Lockheed and Mathematica to perform the Space Tug Economic Analysis study is illustrated in Figure 2-1, a highly simplified diagram of study data flow. As this figure shows, there were three major steps in the analysis:

1. Building the data base (Lockheed task)
2. Integrating the data and interpreting the processed information (Lockheed task)
3. Performing the economic analysis (Mathematica task)

DATA BASE APPROACH

The data base comprised: (1) design and cost data for the candidate Tug concepts, and (2) design and cost data for the unmanned spacecraft in the mission model. The nature and extent of information contained in the data base is summarized in the following paragraphs.

Tug Data Base

The principal sources of information used in building the Tug data base were prior and concurrent Tug studies and internal Lockheed analyses of space propulsion stage designs and costs. These elements of the data base were then normalized, i.e., adjusted for differences in constraints, guidelines and assumptions, so that all designs and cost information conformed to a common baseline. Finally, the normalized data were used to synthesize reference concepts on which further data base work could be founded.

From the standpoint of design and cost data, the orbit injection stages (OIS) were treated as point designs because existing OIS vehicles have established sizes and their growth versions are fairly well defined. The reusable Space Tugs were treated

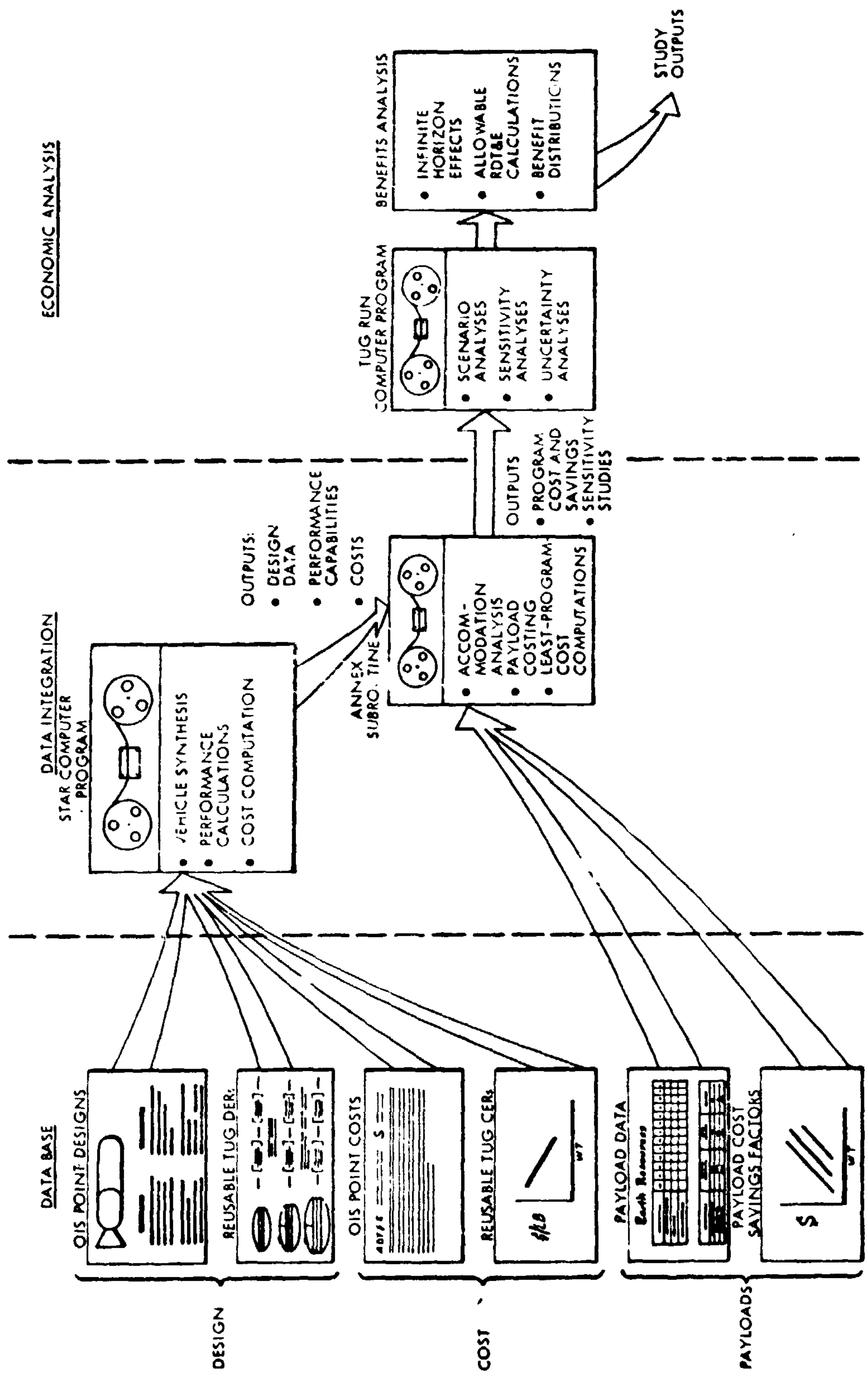


Figure 2-1. Overall Study Approach

parametrically in the design and cost data bases so that sizing variations could be considered along with other configuration operations and variables.

To produce the parametric design and cost data needed for analysis of reusable Space Tug configurations, the following steps were taken:

- Design: A system of parametric design estimating relationships (DERs) was generated for the various Tug propellant combinations, vehicle configurations, and basing modes. The DERs established the weights and dimensions of candidate Tugs as a function of propellant loading and flight mode. Weights and sizes were calculated using a detailed methodology that evaluated stage hardware down to major-assembly and in some cases compenent level.
- Cost: A Space Tug cost model was derived for this study. This model uses parametric cost estimating relationships (CERs) based on historical data, together with algorithms that reflect relative complexity factors, learning effects, and activity-level relationships. It calculates Tug RDT&E, investment (fleet buy), and operations costs based on inputs characterizing the design and weights of the particular Tug concepts.

Payload Data Base

The final element in the data base was information on the payloads delivered by the Space Tug system. A mission model comprising 64 programs (483 spacecraft placements) was supplied to Lockheed as a starting point for this analysis. This model was limited to those missions for which a Tug is potentially required; hence it excluded low-earth-orbit spacecraft directly deliverable by the Shuttle alone. User agencies represented in the model were NASA (both the Office of Space Sciences and the Office of Applications), the Department of Defense, and various non-NASA applications agencies.

The orbital parameters, sizes, weights (by subsystem), power requirements, and flight schedules were tabulated for the baseline payloads supplied in the mission model. The costs for these baseline payloads were then calculated using a parametric cost methodology applied to the spacecraft weights and characteristics; the resulting costs were checked against comparable estimates derived by Aerospace Corporation in the Space Transportation System Economic Analysis study and found to be in agreement.

Having established the baseline payload costs, the final step in the data base task was to develop algorithms to express the payload savings possible with Space Tug systems. Based on the work performed by Lockheed under the original Payload Effects Analysis study (NASw-2156) three classes of payload cost savings were identified for the Tug, namely:

- Mass/Volume. These are the savings possible when payload weight and volume capacity (in excess of baseline requirements) are available, and low-cost fabrication techniques can be used because of the relaxed design tolerances.
- Payload Retrieval and Reuse. These are savings achieved when a spacecraft retrieved from orbit is refurbished, experiments are replaced as needed, and the spacecraft is returned to operational service (in lieu of purchasing a new unit).
- Accessibility. These savings, formerly called risk acceptance, arise from the fact that less testing (both RDT&E and acceptance) can be allowed for spacecraft that are accessible for repair in case of failure on orbit.

The savings attainable with each of these three effects were quantified in the form of cost and weight estimating relationships, and other algorithms.

DATA INTEGRATION AND INTERPRETATION

The process by which Lockheed processed and interpreted information from the data base involved a close man/machine interaction. Simple, high-speed computer programs were used extensively so that the widest possible number of variables could be incorporated into the analysis while maintaining a short turnaround time for individual cases. Lockheed used as its primary computer program the Space Transportation Analysis Routine (STAR) and a subroutine designated ANNEX that calculates totals program costs. STAR and ANNEX are not optimization programs, but rather computational tools designed to extend the efficiency of systems engineers. Individual runs of STAR/ANNEX were made for each Tug configuration or sensitivity variation being studied. At the conclusion of each sequence of runs the data evaluation team reviewed STAR/ANNEX printouts to determine cost-driving factors such as the number of Shuttle flights, Tug flight-mode shifts, and Tug inventory requirements.

Specific functions performed in the STAR/ANNEX program were as follows:

- Reusable Tug Design Synthesis. Using the parametric design estimating relationships supplied from the data base, reusable Space Tug configurations (and expendable versions thereof) were synthesized for propellant loadings and flight modes of interest in the study. Detailed (65-entry) weight summaries were generated and Tug dimensions were calculated for the selected configurations. Mass fractions were computed for all Tug concepts.

- Performance and Mission-Accommodation Analysis. Using the stage mass fraction data from the Design Synthesis routine, the performance capabilities of candidate Tugs and orbit injection stages were calculated for all applicable Tug flight modes and staging techniques. The Tug performance data was then integrated with Shuttle performance data (supplied by NASA), and reference payload weights and sizes (from the payload data base). In this way there was formulated a mission-by-mission assessment as to which payloads could be flown in which modes with a given Tug. Any excess payload capability was also noted.

- Tug Cost Analysis. The next step in the STAR/ANNEX logic was calculation of the Tug costs. OIS costs were entered directly because these were point values. Reusable Tug costs were calculated using the Space Tug cost model that was mechanized in STAR; this cost model used as input the weights and characteristics generated in the Vehicle Synthesis routine. Activity-level-dependent costs were calculated on the basis of preliminary fleet sizes and activity levels projected in the Accommodation Analysis.

- Payload-Effects and Total-Program-Cost Analysis. At this point the potential payload cost savings were calculated and the relative total-program costs (Tug costs, Shuttle user fees, payload costs) were computed. The logic of this routine was as follows. For any given Tug concept, STAR/ANNEX progressed through the mission model one program at a time. Using data on Tug capabilities and payload requirements established in the Accommodation Analysis – along with the payload-cost savings algorithms developed in the data base – the payload and transportation costs were calculated (on a discounted basis) for every flight mode under every mission. A mode-by-mode comparison was made to arrive at the least-cost way of performing each program in the mission model, and the resulting cost for the total program was, by definition, the least-cost way to apply a given Tug to the reference mission model under the stipulated set of variables (e.g., Shuttle user fee, Tug lifetime, stage design).

- Total Cost and Funding Requirements Analysis. This final routine in STAR/ANNEX produced a refined total-program cost plus the annual funding requirements for the given Tug and the given variables. The first step in this analysis was to recompute Tug activity-level-dependent costs based on the least cost mode mix derived in the previous step. These Tug operations costs were added to the Tug RDT&E and investment costs, the Shuttle user costs, and the payload costs to arrive at a total-program cost figure. This sum was time phased, using RDT&E and procurement spans along with standard statistical spread functions, to arrive at funding requirements by fiscal year.

ECONOMIC ANALYSIS

Mathematica received direct outputs from the STAR/ANNEX program in punched-card format, and also hard copy printouts of the STAR/ANNEX runs. From this data base, Mathematica proceeded to process and interpret the Tug systems data from a purely economic point of view.

The Mathematica approach to data analysis, as did the Lockheed approach, featured a close man/machine interaction. Mathematica used a computer program called TUGRUN, adapted from an earlier version called SCENARIO, to mechanize the performance of economic sensitivity analyses. Using TUGRUN, the following sensitivity analyses were performed.

Programmatic Variables

- Mission Scenario
- Shuttle User Fee
- Payload Refurbishment Factor
- Payload Cost Uncertainty

Tug System Variables

- Tug RDT&E Cost Uncertainty
- Tug Operations Cost

The outputs of TUGRUN were evaluated and interpreted manually. Additional runs were made to expand or clarify the analysis.

Other elements of the Mathematica economic analysis were performed manually. These included the calculation of allowable RDT&E costs and the analysis of Tug program benefits. Allowable RDT&E costs were computed in the following way:

1. Tug recurring cost benefits (i.e., savings in payload and transportation costs referenced to the best orbit injection stage) were calculated at a 10 percent discount rate.
2. These benefits were extended indefinitely in time by the so-called "infinite horizon" technique.

3. The discounted benefits were summed and converted back to undiscounted costs spread across the time period in which RDT&E expenditures would be made. This gave the allowable RDT&E expenditures, referenced to the baseline OIS vehicle; by subtracting the estimated RDT&E costs for a particular Tug concept from the allowable values, an economic margin was derived to express the net advantage or disadvantage of that concept.

Mathematica also analyzed the distribution of benefits by user agency, energy level, and source, as well as by time-phasing.

To approach the problem of Tug time phasing and fleet-mix composition, Mathematica developed (through feasibility demonstration) a computer program called OPCHOICE. This program used mixed-integer programming techniques.

DATA BASE

Chapter 3
DATA BASE

The contents, structure, and level of detail of the data base are formulated to provide an information system that will adequately support attainment of the study objectives. The data base consists of both the tabular data and analytical equations necessary for synthesizing and simulating the design, cost, payload, and performance aspects of the candidate Space Tug configurations. It is structured to support the interface and retrieval requirements of the computer software employed in the study and to provide traceability and visibility of data through the analyses to the study results. Because of the interrelationships between the disciplines supported by the data base, a constraint is imposed on the level of detail of each of the data elements to maintain consistency of data. Consequently, the synthesis of Tug designs and costs is compatible, as is the design definition and the performance equations.

Each element of the data base, its contents and structure, is discussed in the following paragraphs.

DESIGN DATA

The first element of the data base consists of the design data necessary to synthesize the current and advanced Space Tug concepts considered in the study. The design data is composed of point designs for the orbit injection stages (OIS) and parametric design estimating relationships (DER) for the reusable Space Tug concepts. Point designs were used for the OIS because the existing vehicles are of established size and their growth versions are defined. The use of DERs for the reusable Tug concepts is a consequence of the study objective to determine the optimal size (from an economic standpoint) of these vehicles.

Orbit Injection Stages

The two classes of OIS vehicles configured in the data base are the current and improved versions of the Agena and Centaur. The Agena configuration represents an interim definition from the LMSC Shuttle/Agena Compatibility Study. (An interim configuration was used because of the overlap between these studies and the need for the Agena configuration early in the Space Tug Economic Analysis.) The Agena OIS is an inertially guided, earth-storable stage featuring a common bulkhead with integral (load carrying) propellant tankage. The length and diameter of this stage are 20.7 and 5.0 feet, respectively. A summary of the propulsion characteristics for this stage and its weight breakdown are presented in Table 3-1. A detailed description of this vehicle is presented in the final report of the Shuttle/Agena Compatibility Study (NAS9-11949, February 1972).

The growth version of the Agena, designated Large Tank Agena (LTA), is a 10-foot diameter stage about 26 feet in length. The LTA propulsion improvements (e.g., 75:1 nozzle expansion ratio) coupled with the use of high density acid as the oxidizer yield a 19 sec increase in stage specific impulse. A summary of the propulsion and weight characteristics for the LTA are presented in Table 3-2. A typical LTA configuration is presented in Figure 3-1.

The Centaur OIS configuration (Figure 3-2) is a long-coast-life (5.25 hours) version of the standard D-1T Centaur modified for launch in the Space Shuttle. It has a diameter of 10 feet and length of 32 feet. This LO_2/LH_2 stage has a common bulkhead tank arrangement and is powered by a pair of Pratt and Whitney RL10 engines. A summary of the propulsion characteristics for this stage and its weight breakdown are presented in Table 3-3.

The growth version of the Centaur, designated Growth Tank (GT) Centaur has a 45,000 lb propellant load and uses the same propulsion system as the D-1T configuration. The weight characteristics for this stage are summerized in Table 3-4.

Table 3-1. AGENA OIS CHARACTERISTICS

Main Propulsion System	
Designation	8096 Bell Engine (Multi-Start)
Fuel	Unsymmetrical Dimethylhydrazine
Oxidizer	Inhibited Red Fuming Nitric Acid
Mixture Ratio	2.53:1 (O/F)
Specific Impulse	290.8 sec
Vacuum Thrust	16,100 lb
Expansion Ratio	45:1
Minimum Impulse Bit	23,750 lb-sec

Reaction Control System	
Propellant Type	N_2 (cold gas)
Vacuum Thrust	10 lb (max)
Specific Impulse	67 sec (max)

Weight Breakdown	
Subsystem	Weight (lb)
Structure	496.0
Electrical Power	200.0
Propulsion	329.0
Communication	41.0
Guidance and Control	101.0
Reaction Control System	58.0
Total Stage Dry Weight	1,225.0
Helium Gas	2.5
Nitrogen Gas	30.3
Propellant Loaded (UDMH/IRFNA)	13,400.0
Total Ignition Weight	14,657.8

Table 3-2. LARGE TANK AGENA CHARACTERISTICS

Main Propulsion System	
Designation	8096 Bell Engine (Multi-Start)
Fuel	Unsymmetrical Dimethylhydrazine
Oxidizer	High Density Acid (Nitric Acid & Nitrogen Tetroxide)
Mixture Ratio	2.66:1 (O/F)
Specific Impulse	310 sec
Vacuum Thrust	17,620 lb
Expansion Ratio	75:1
Minimum Impulse Bit	23,750 lb-sec

Reaction Control System	
Propellant Type	N_2 (cold gas)
Vacuum Thrust	10 lb (max)
Specific Impulse	67 sec (max)

Weight Breakdown	
Subsystem	Weight (lb)
Structure	875.0
Electrical Power	180.0
Propulsion	421.0
Communication	45.0
Guidance and Control	163.0
Contingency	170.0
Total Stage Dry Weight	1,854.0
Helium Gas	10.0
Nitrogen Gas	30.0
Propellant Loaded (UDMH/HDA)	48,800.0
Total Ignition Weight	50,694.0

Table 3-3. CENTAUR OIS CHARACTERISTICS

Main Propulsion System	
Designation	RL10A-3-3
Fuel	Liquid Hydrogen
Oxidizer	Liquid Oxygen
Mixture Ratio	5:1 (O/F)
Specific Impulse	444.0 sec
Vacuum Thrust	15,000 lb
Expansion Ratio	57:1
Minimum Impulse Bit	24,000 lb-sec
Reaction Control System	
Propellant Type	Hydrogen Peroxide
Vacuum Thrust	4 at 5.2, 4 at 3.0, 2 at 6.0, and 4 at 3.5 lb
Specific Impulse	155 sec
Weight Breakdown	
Subsystem	Weight (lb)
Body Group	1,523.0
Propulsion Group	971.0
Flight Control Group	312.0
Fluid Systems	326.0
Electrical Group	144.0
Reaction Control	196.0
Information System	292.0
GDCA Truss Adapter	95.0
Separation Equipment	45.0
Total Stage Dry Weight	3,904.0
Propellant Load	30,584.0
Total Ignition Weight	34,488.0

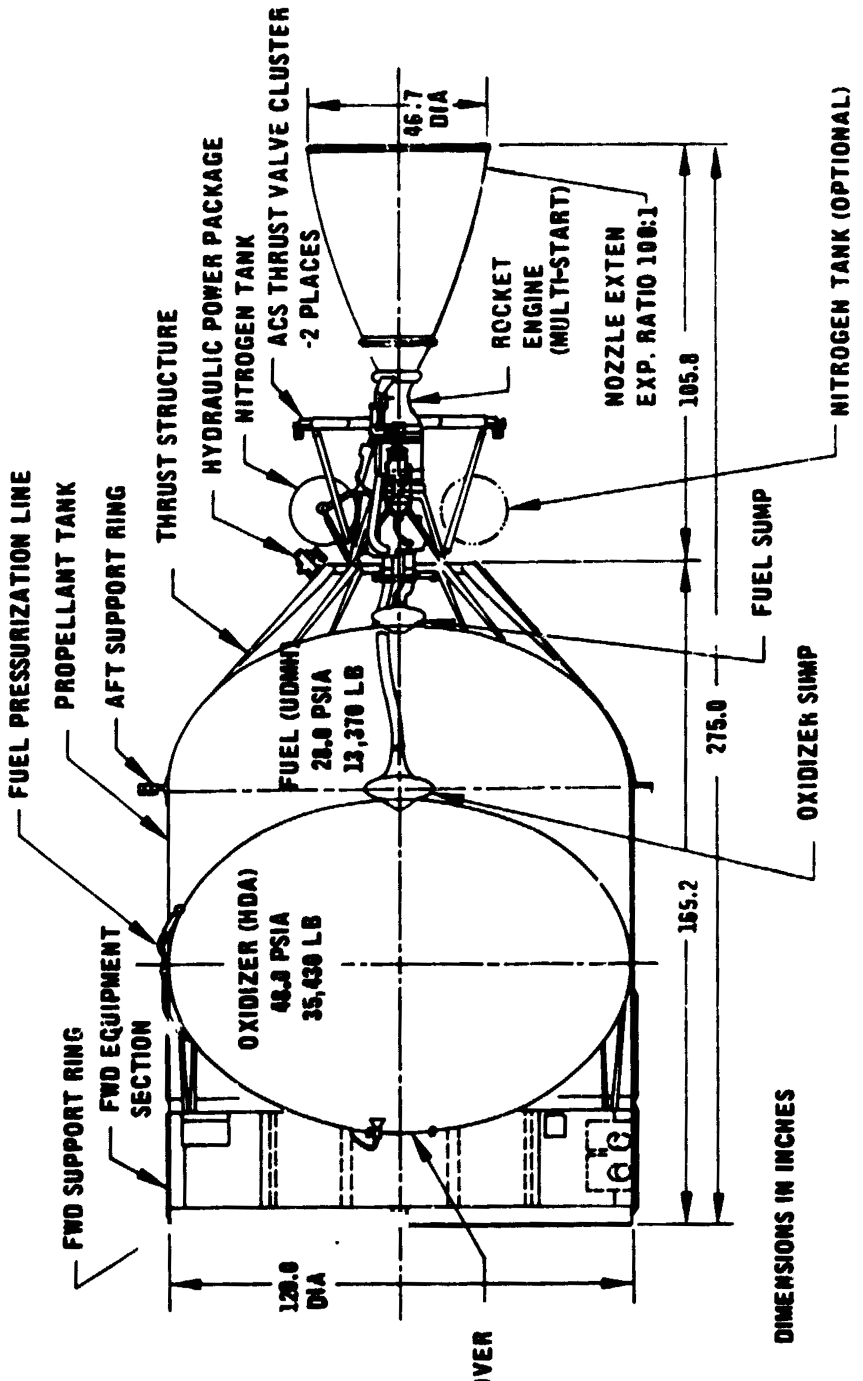


Figure 3-1. Large Tank Agena Orbit Injection Sta...

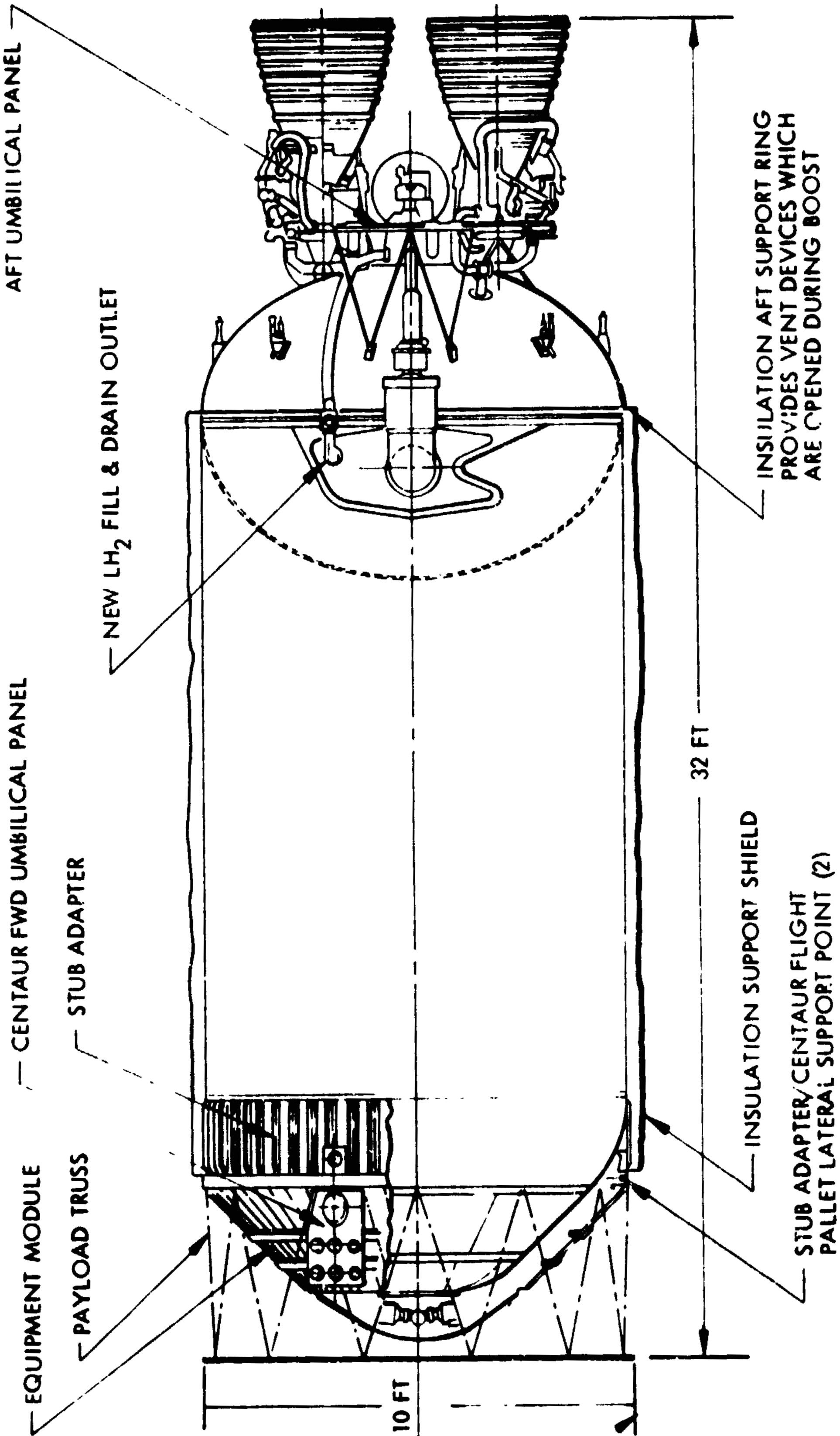


Figure 3-2. Centaur OIS Configuration

Table 3-4. GT CENTAUR OIS WEIGHT BREAKDOWN

Subsystem	Weight (lb)
Body Group	1,854.0
Propulsion Group	1,016.0
Flight Control Group	311.0
Fluid Systems	373.0
Electrical Group	148.0
Reaction Control	133.0
Information System	298.0
Mission Peculiar Hardware	83.0
Separation Equipment	36.0
Total Stage Dry Weight	4,252.0
Propellant Load	45,624.0
Total Ignition Weight	49,876.0

Reusable Space Tugs

Because it is necessary to analyze the reusable Tug concepts parametrically, sets of design estimating relationships (DERs) were generated for the various Tug propellant combinations, vehicle configurations, and basing modes. The DERs establish the weights and dimensions of candidate Tugs as a function of propellant loading and flight mode. Weights and sizes are calculated using a detailed methodology that evaluates stage hardware down to major assembly or even component level.

Because the Space Tug design is still in the conceptual stage (studies have been and are being performed by different government agencies and contractors), no definitive Tug design was available to use in this study. Therefore, prior to developing the design estimating relationships for each Tug subsystem, representative vehicle configurations and subsystems were selected based on prior Tug studies and in-house LMSC work. The Tug configuration and subsystems shown in Figure 3-3 are meant to be typical only. However, they do represent reasonable engineering selections

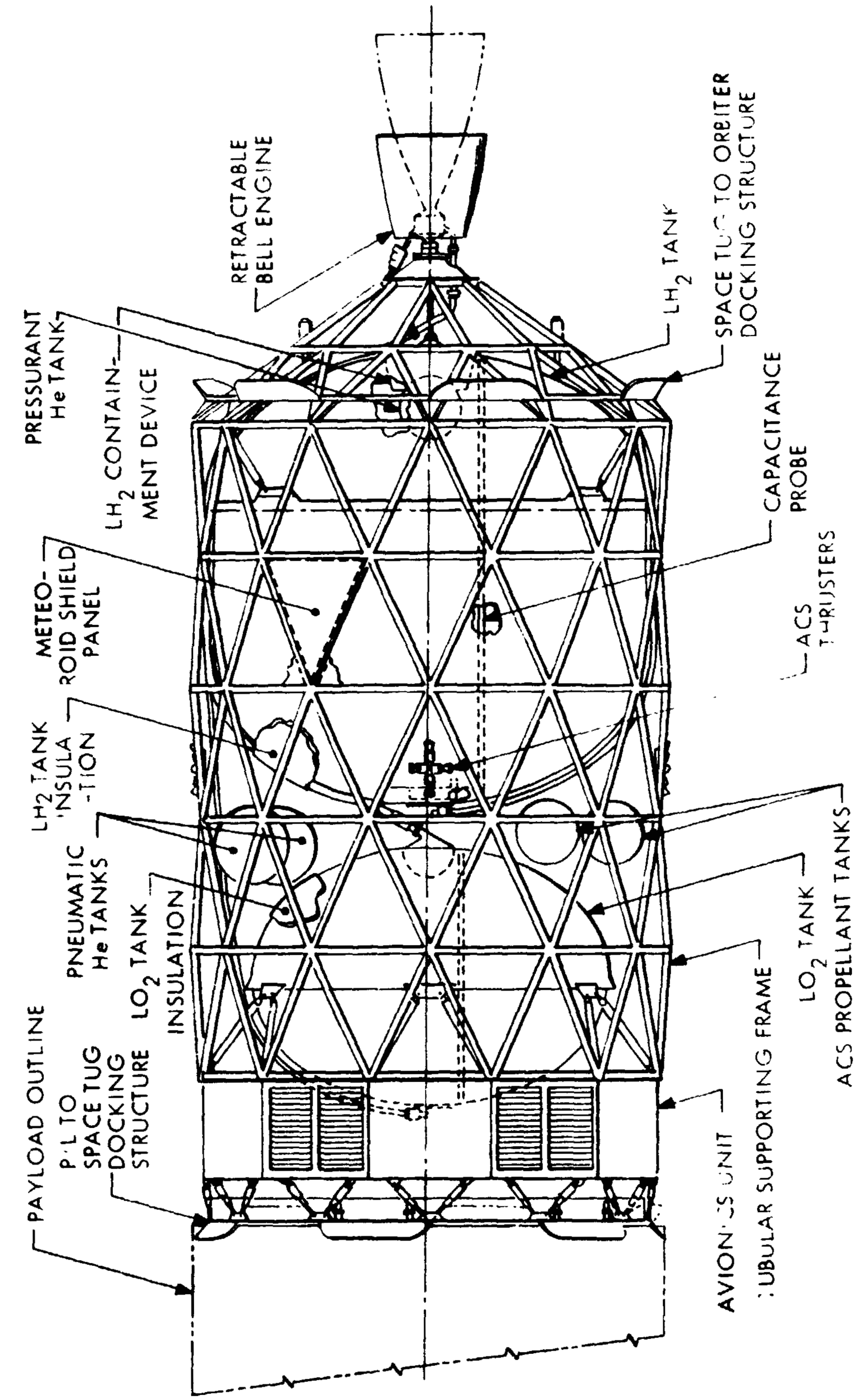


Figure 3-3. Typical Reusable Tug Design

based on past trade-off studies and do serve as a baseline for the scaling equations that were developed. Characteristics of the Tug subsystems that were selected are summarized below:

Safety factor = 1.4 on ultimate (2.0 for high pressure bottles; 4.0 for plumbing systems)

Design concepts whose basic feasibility has been demonstrated and which can be available for flight use by 1979

Variable propellant loading from 20,000 to 70,000 lb

Retractable Bell engine, 1 ea (10K to 30K thrust)

Truss load-carrying structure

Two $\sqrt{2}$ ellipsoidal tanks (for the expendable drop tank set, multiple spherical LO_2 tanks were used with one $\sqrt{2}$ LH_2 tank)

Fiberglass support struts

Microsphere load-bearing insulation with thin metal vacuum jacket for reusable vehicles (Purged fiberglass batting for the tank set)

N_2O_4/MMH reaction control system

Pressurization system (idle-mode start, temperature controlled)

- GH_2 for LH_2 tank
- GHe for remaining tanks

Non-structural meteoroid bumpers (removable) with 0.99 probability of no puncture

Vented LH_2 and CH_4 tank; remaining tanks non-vented. LO_2, LF_2 tanks cooled with boiloff GH_2

Thermal conditioning unit (TCU) type zero-g vent system for LH_2 tank and CH_4 tank

Power supply: nonaqueous lithium batteries, or fuel cells

Avionics support ring at forward end of Tug

Active payload docking adapter

Passive Shuttle docking ring

The conservative nature of these DERs may be seen by comparing a weight statement generated with the scaling equations to designs resulting from the McDonnell Douglas (McDAC) and North American Rockwell (NAR) Space Tug point design studies. This comparison is presented in Table 3-5 for a 54,000 lb LO_2/LH_2 propellant weight. Note that the reference Tug weights used in the study are consistently higher than those of

Table 3-5. COMPARISON OF REUSABLE TUG POINT-DESIGN WEIGHTS
GROUND BASED, LO_2/LH_2

	STUDY VALUE	McDAC POINT DESIGN	NAR POINT DESIGN
STRUCTURES	(2,560)	(2,097)	(1,769)
FUEL TANK	602	372	373
OXIDIZER TANK	263	223	319
SLOSH BAFFLES	52	0	Incl. Above
OUTER FRAME/SHELL	540	946	742
THRUST STRUCTURE	210	68	30
TANK SUPPORTS	118	148	44
EQUIPMENT MOUNTING STRUCT.	399	0	100
DOCKING MECHANISMS	376	106	100
METEOROID SHIELD	0	183	46
MISC	0	51	15
THERMAL PROTECTION	(674)	(383)	(275)
PROPULSION	(997)	(1,236)	(924)
MAIN ENGINE	357	218	230
PRESSURIZATION/FEED/FILL	353	419	334
REACTION CONTROL	287	599	360
AVIONICS	(1,023)	(724)	(869)
DATA MANAGEMENT	43	80	120
GUIDANCE, NAVIGATION AND CONTROL	386	187	208
COMMUNICATIONS	112	75	55
INSTRUMENTATION	20	67	122
ELECTRICAL POWER	275	61	166
ELECTRICAL NETWORKS	187	254	198
CONTINGENCY	525	443	383
DRY WEIGHT	5,779	4,883	4,220
USABLE PROPELLANT	54,020	54,018	54,027
TUG WEIGHT AT SEPARATION	61,577	60,631	59,829
STAGE MASS FRACTION	0.877	0.891	0.903

the McDAC and NAR configurations. The weight differences are primarily in the structures, thermal protection, and avionics systems weights and result from the relatively conservative design philosophy adhered to in the derivation of these equations.

The DERs are incorporated into a computer subroutine which provides a complete synthesis of the weight and geometric characteristics of reusable Tug configurations. The inputs to this routine are Tug mission duration, thrust level, number of engine burns, and the basing mode and Tug operations flags.

This subroutine was employed to generate parametric weight statements and stage geometry for three propellant types, two basing modes, and two engine thrust levels. A representative set of parametric curves, graphed by a computer plotting routine, is presented in Figures 3-4 through 3-18 for a ground-based reusable LO_2/LH_2 Tug. A more complete set of curves and supporting point-design weights is presented in the appendix to Volume II.

The complete Tug data base includes the following cases.

	LO_2/LH_2	LF_2/LH_2	$FLOX/CH_4$
Basing Modes	Ground, Space	Ground, Space	Ground, Space
Thrust	20K, 30K	20K, 30K	20K, 30K
Number of Engine Burns	6	6	6
Operational Mode	Expendable, Reusable	Expendable, Reusable	Expendable, Reusable
Alternative Configurations	Stage-and-one-half, space-based with Augmented Avionics		

The format chosen for the presentation of the stage weight properties is a summed weight approach in which subsystem weights are accumulated in layer-cake fashion to define system and total vehicle weights. Consequently, the distances between the curves in Figures 3-4 through 3-9 represent the weight of the defined subsystems or systems. This format provides a convenient visual aid for comparing the relative magnitude of each of the subsystem components to total system weight and the relative magnitude of each system weight to the total vehicle weight. In Figures 3-10 and 3-11 the parametric stage mass fraction data are presented as a function of impulse propellant. The difference between these two curves is that non-consumable propellants are excluded from the mass fraction calculation in Figure 3-11.

Data on stage geometry as a function of propellant weight are presented in Figures 3-12 through 3-18. These curves include the total stage geometry plus the tank volumes, areas, and lengths.

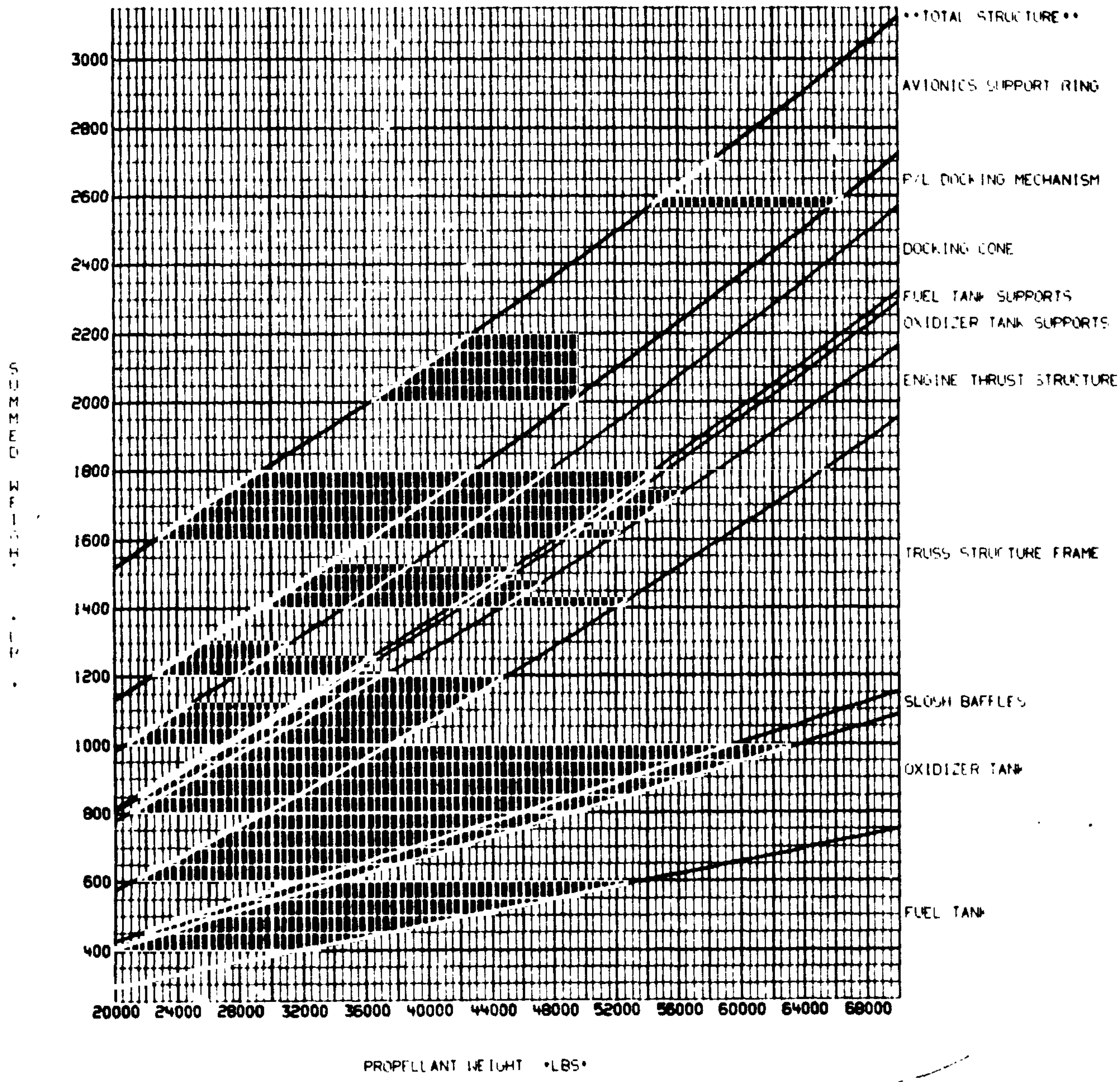


Figure 3-4. Parametric Structures Weight, Reusable LO_2/LH_2 Tug

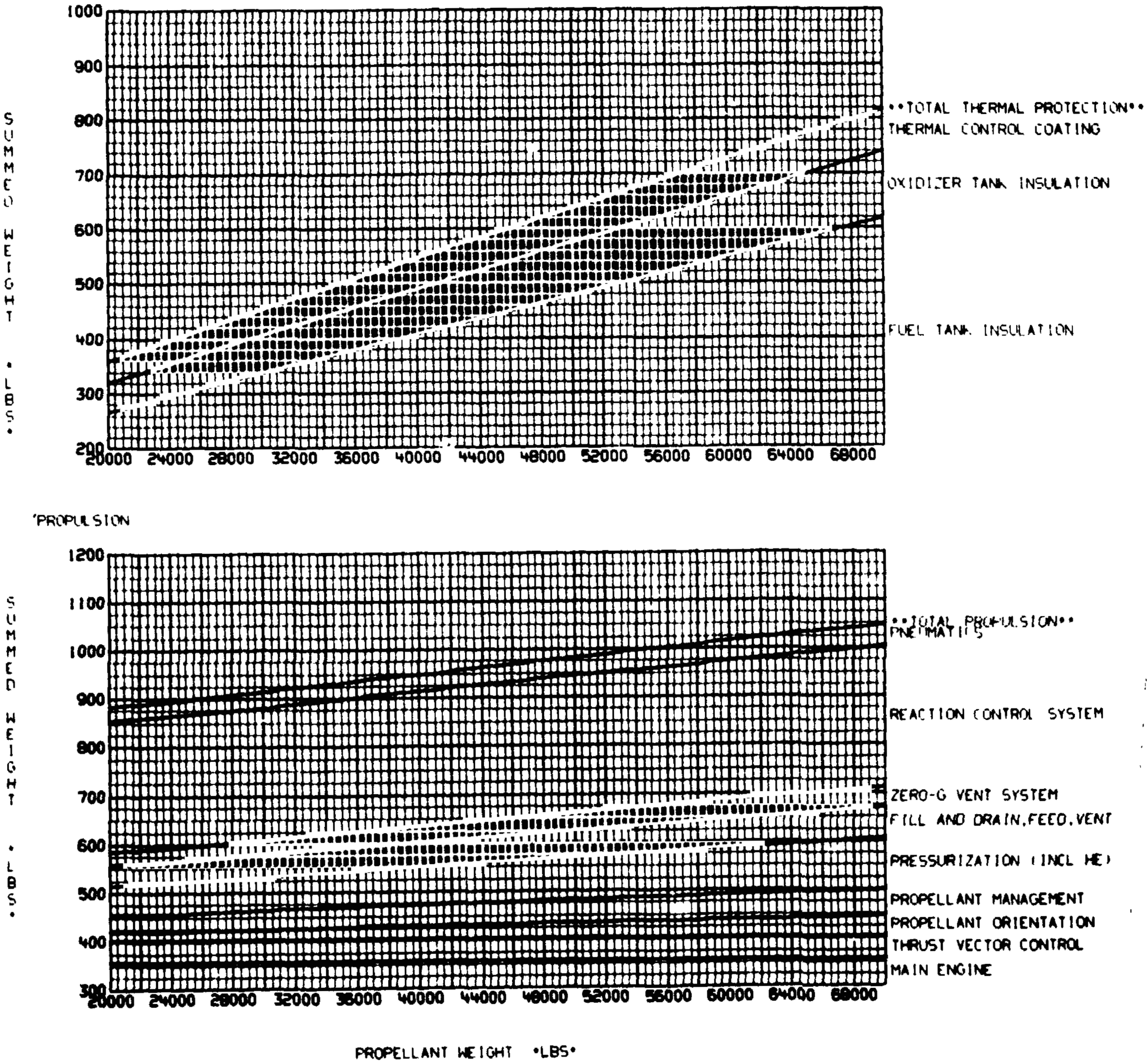


Figure 3-5. Parametric Thermal-Protection and Propulsion Weights, LO_2/LH_2 Reusable Tug

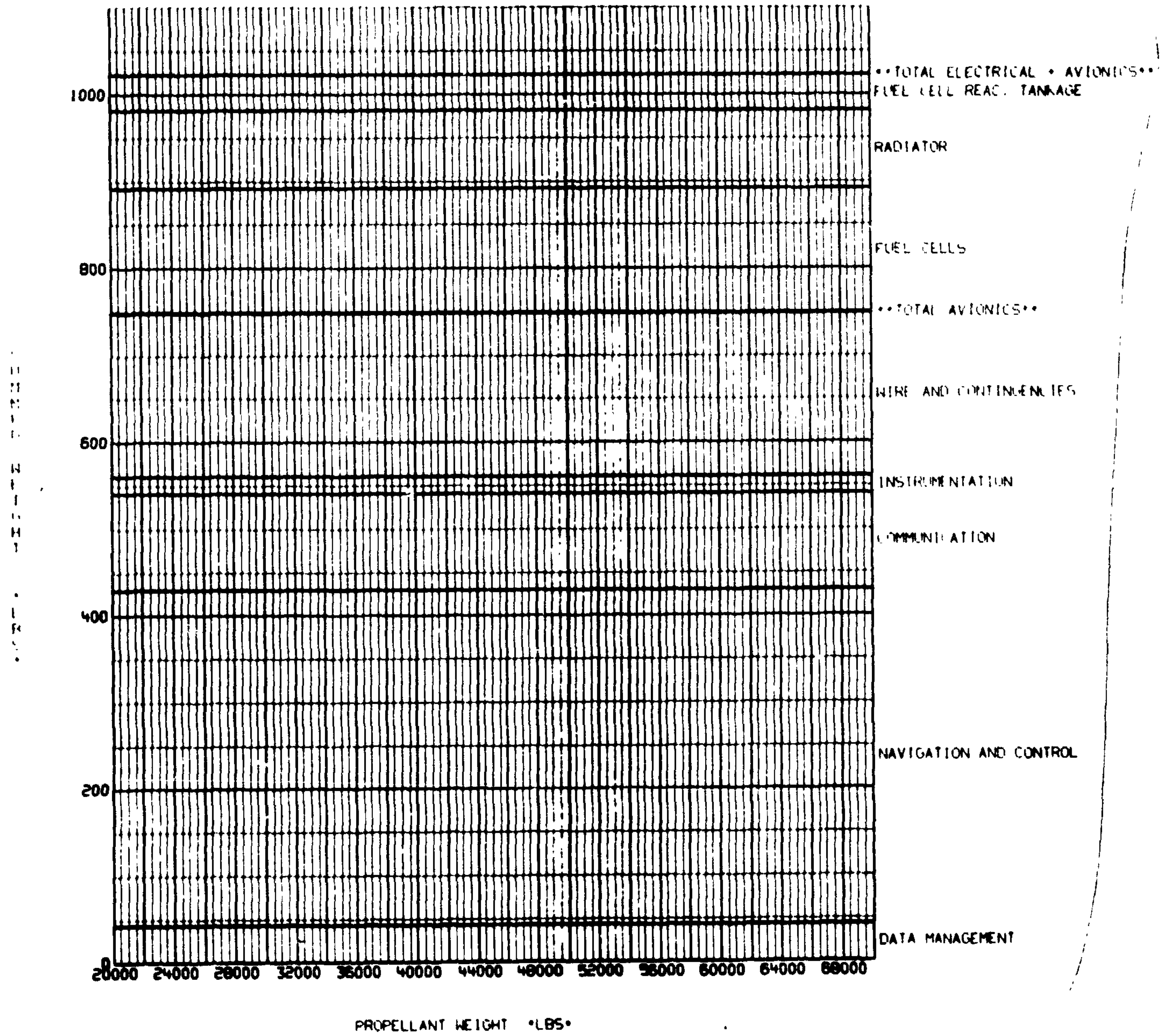
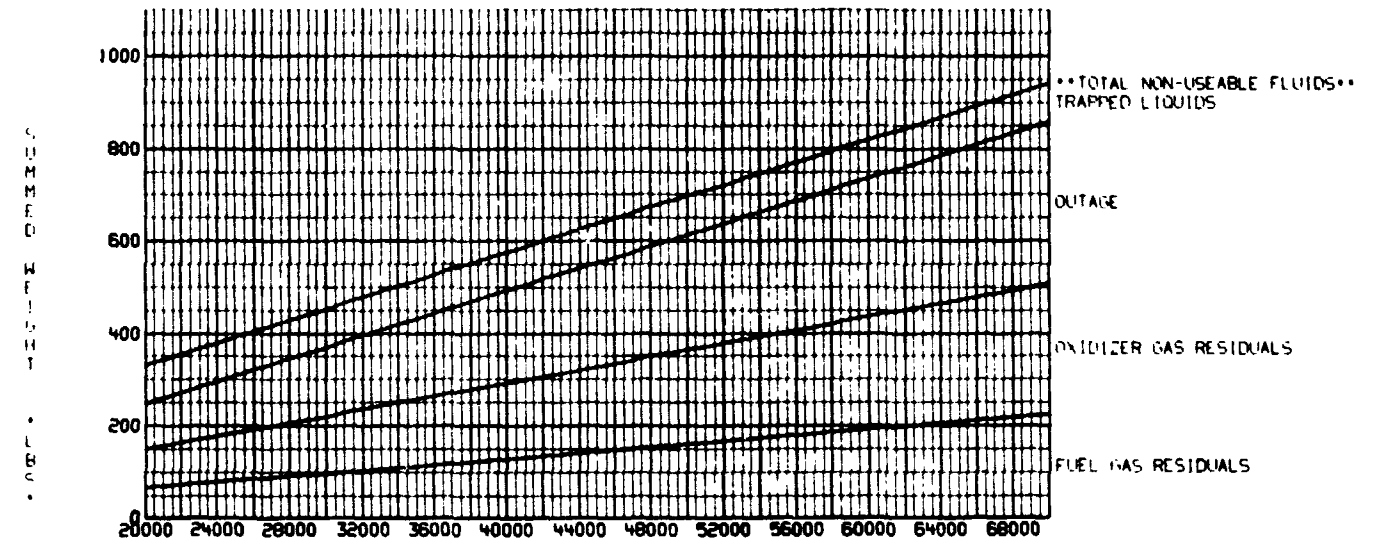


Figure 3-6. Parametric Avionics and Power Subsystem Weights, LO_2/LH_2 Reusable Tug



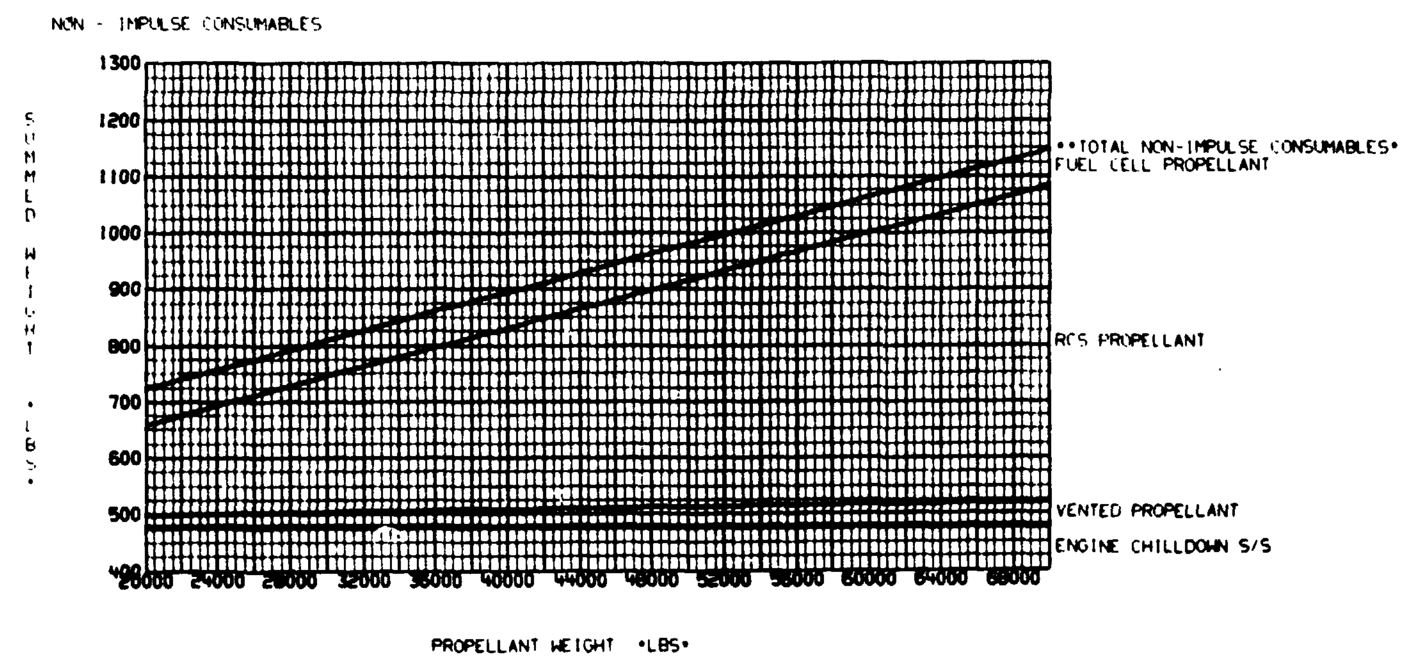


Figure 3-7. Parametric Weights for Non-usable Fluids, LO_2/LH_2 Reusable Tug

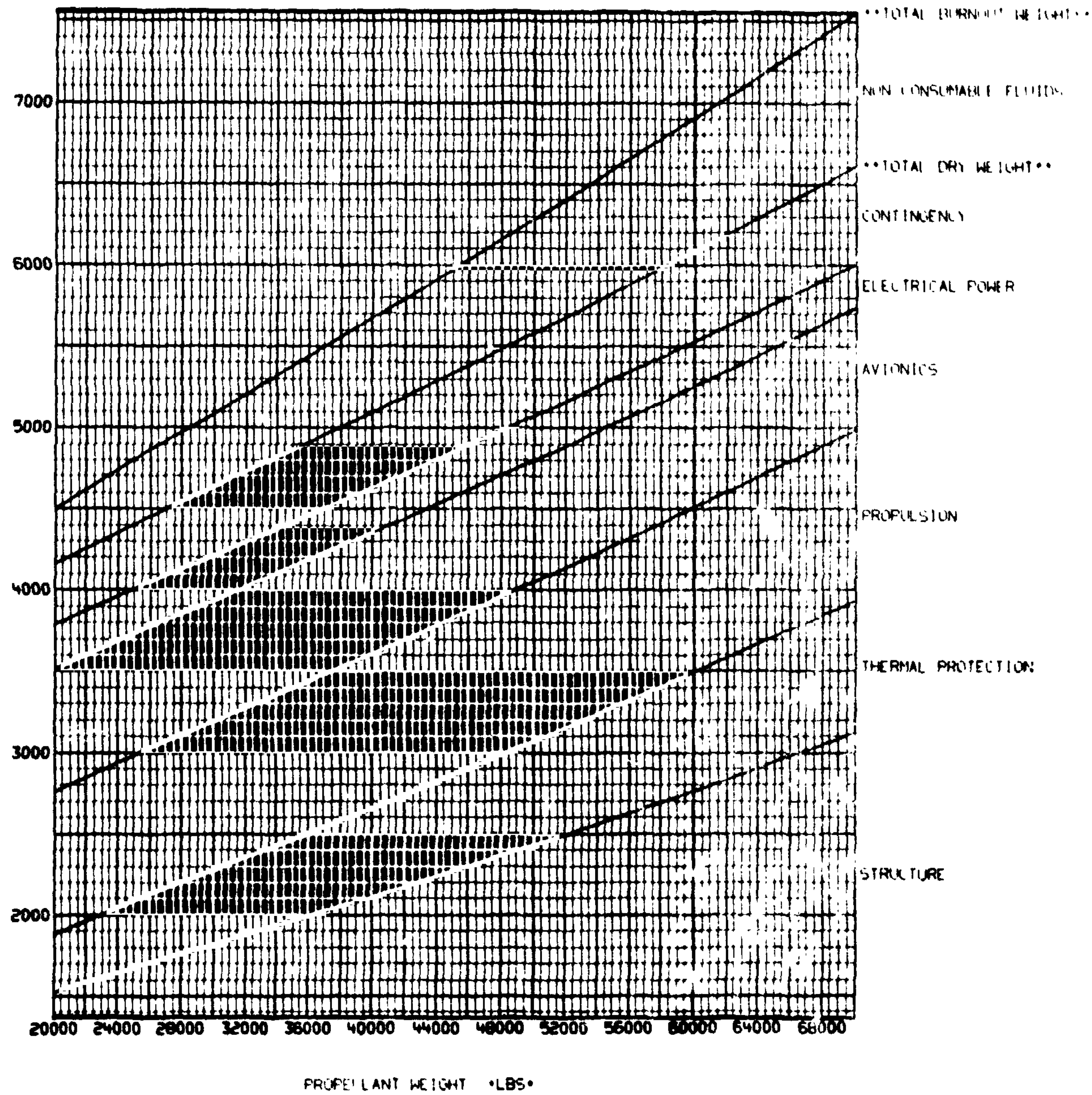


Figure 3-8. Parametric Stage Burnout Weights, LO_2/LH_2 Reusable Tug

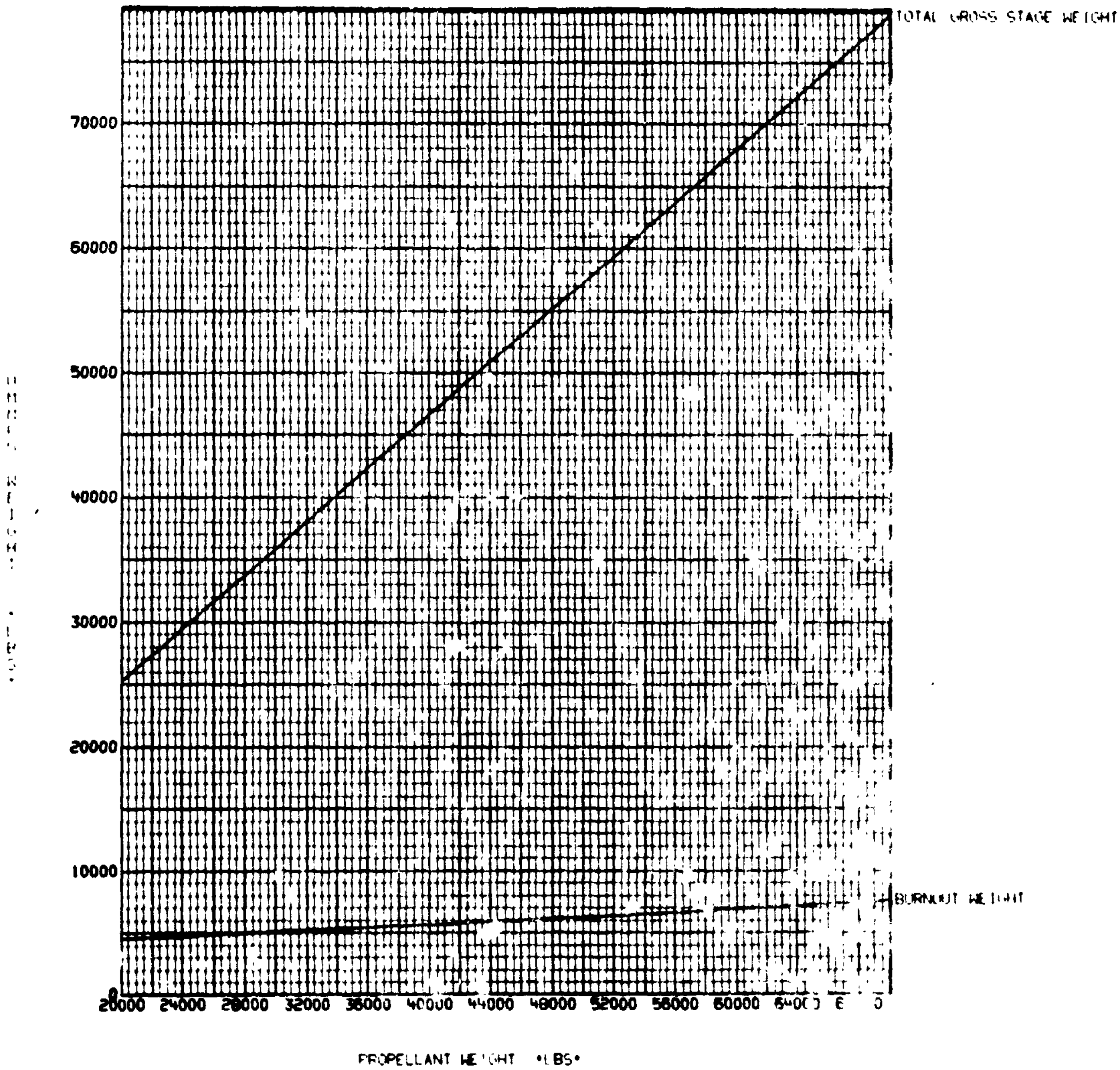


Figure 3-9. Parametric Total-Weight Data, LO_2/LH_2 Reusable Tug

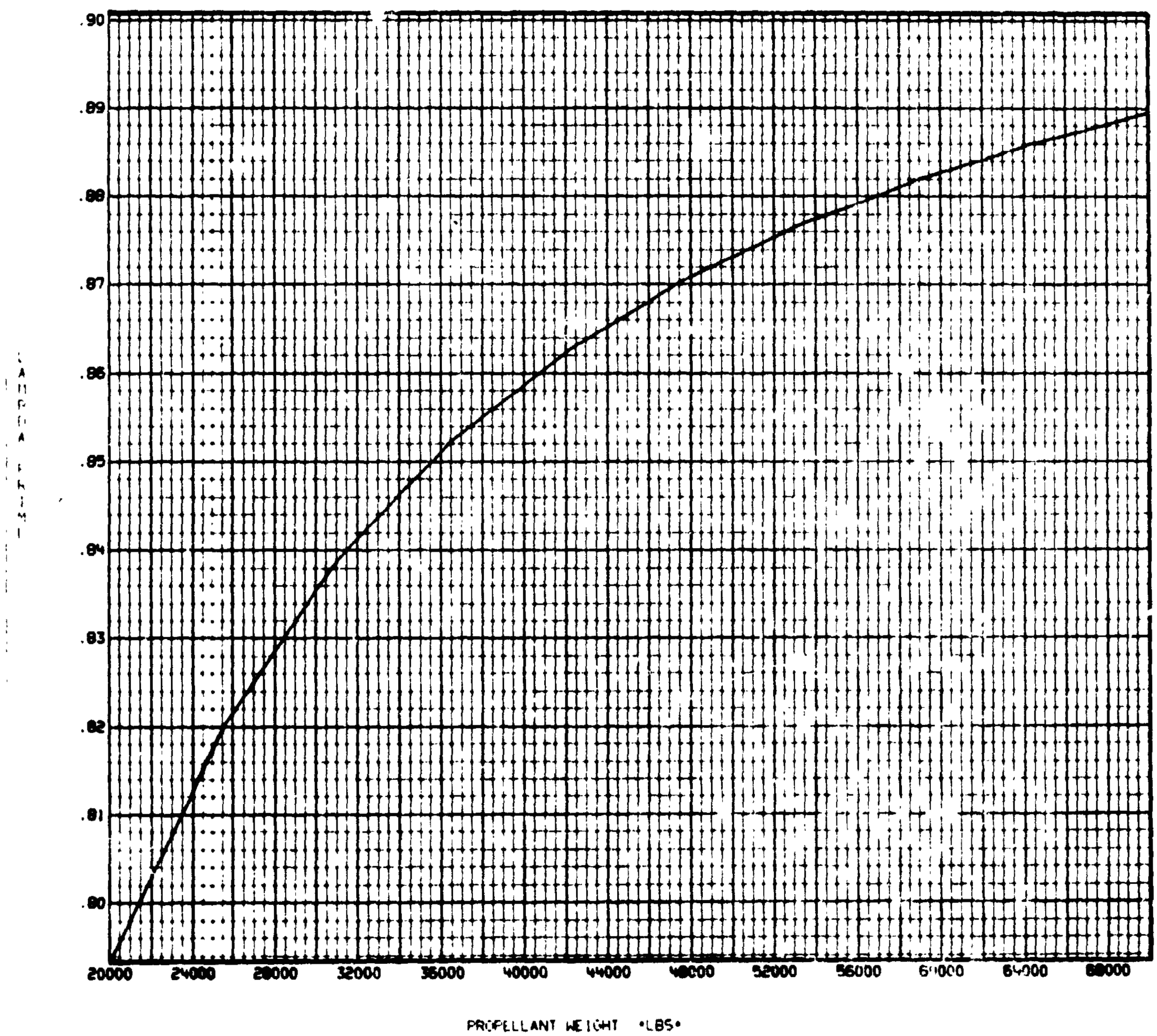


Figure 3-10. Parametric Mass Fraction Data (Based on Total Gross Stage Weight), LO_2/LH_2 Reusable Tug

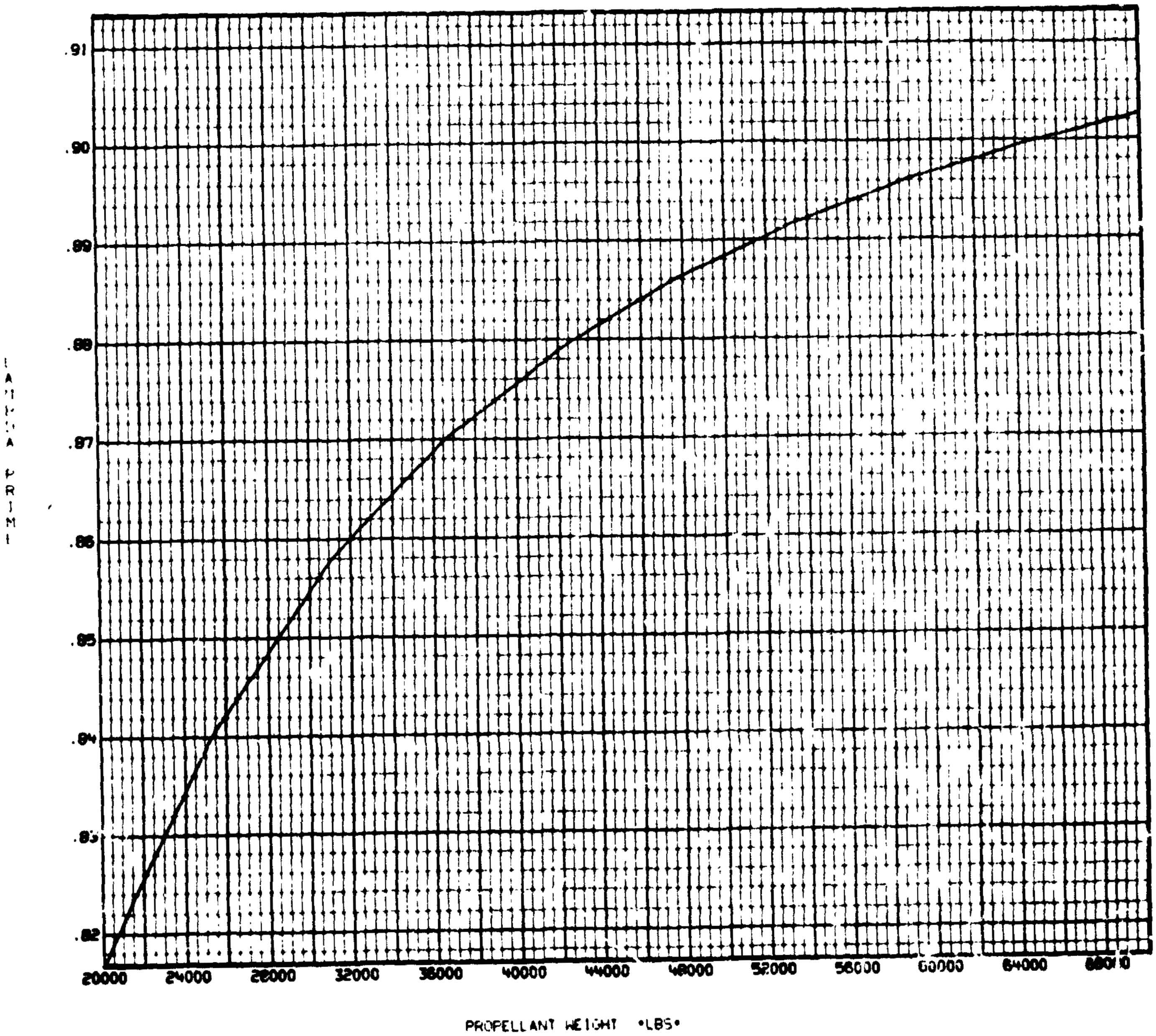


Figure 3-11. Parametric Mass Fraction Data (Based on Burnout Weight and Impulse Propellant), LO_2/LH_2 Reusable Tug

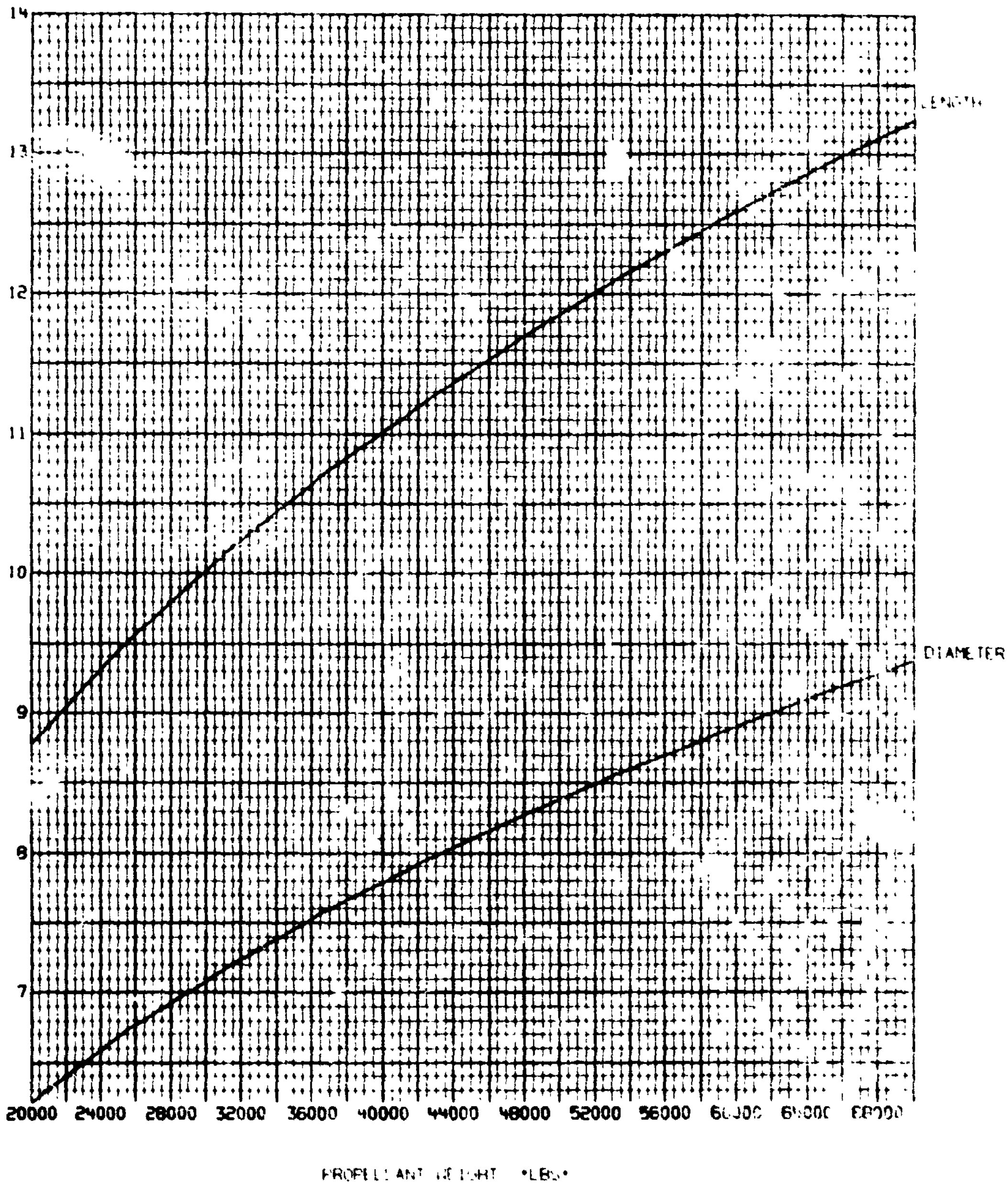


Figure 3-12. Parametric Oxidizer Tank Sizes, Reusable LO_2/LH_2 Tug

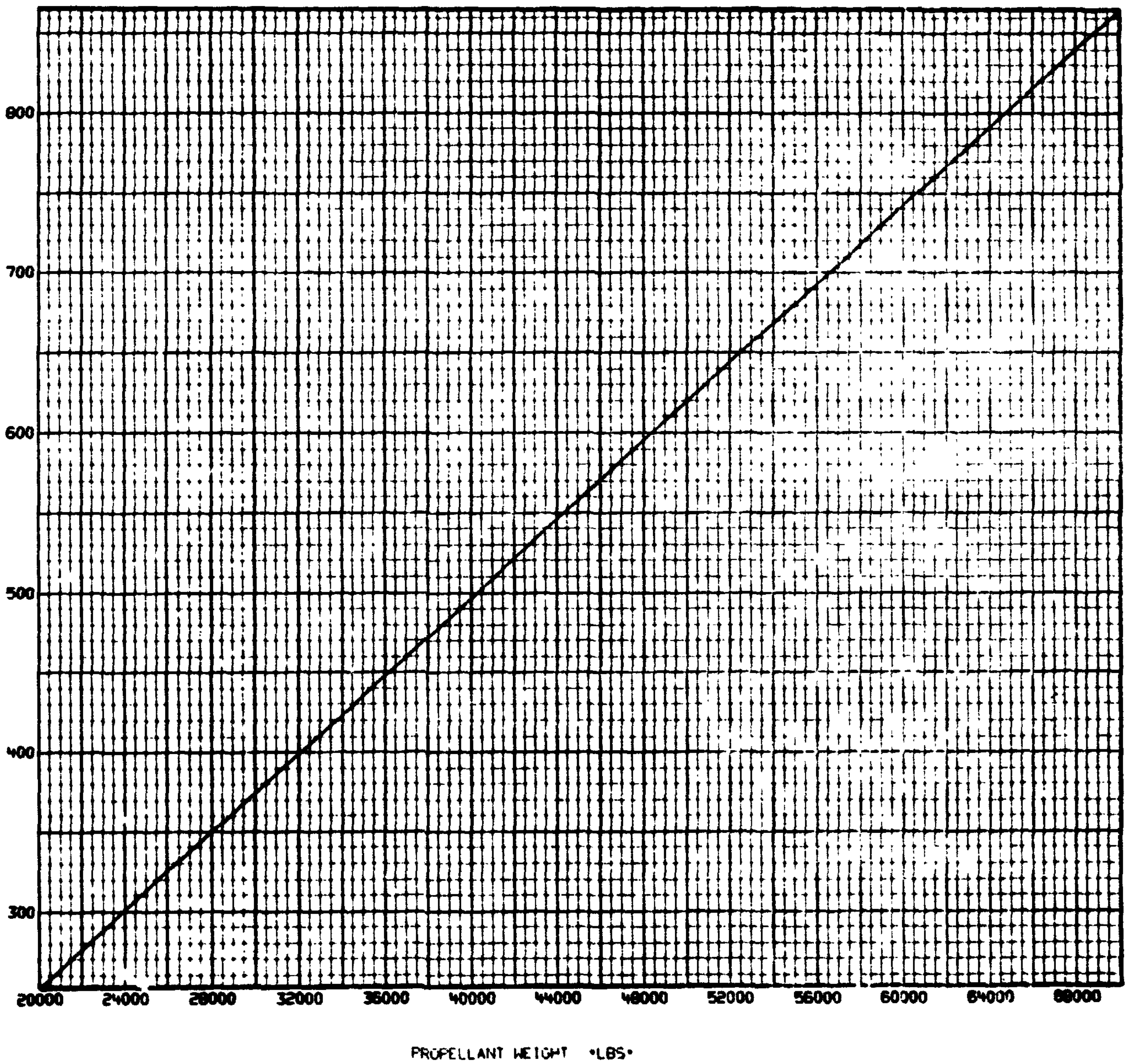


Figure 3-13. Parametric Oxidizer Tank Volume Data, LO_2/LH_2 Reusable Tug

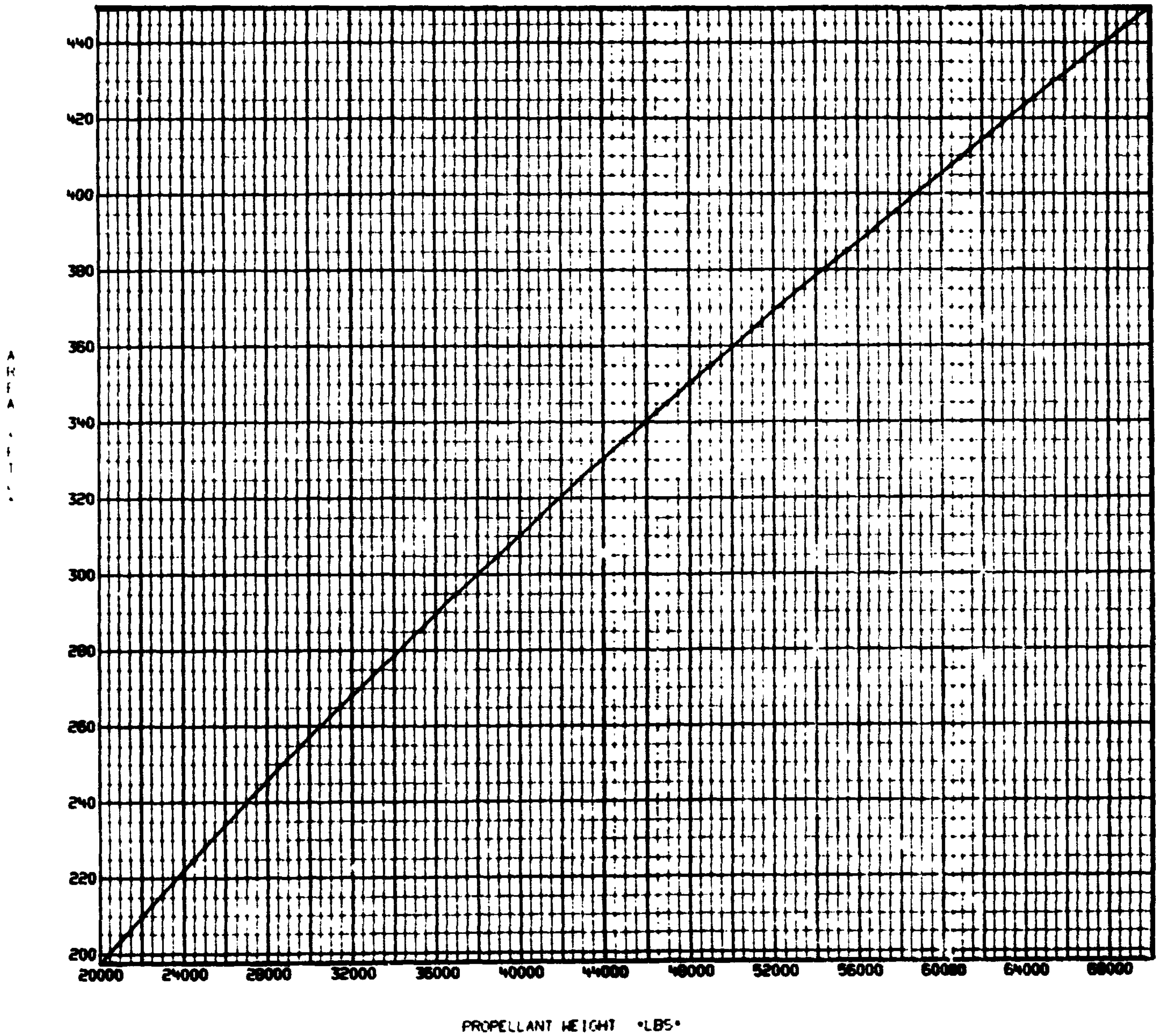


Figure 3-14. Parametric Oxidizer Tank Area Data, LO_2/LH_2 Reusable Tug

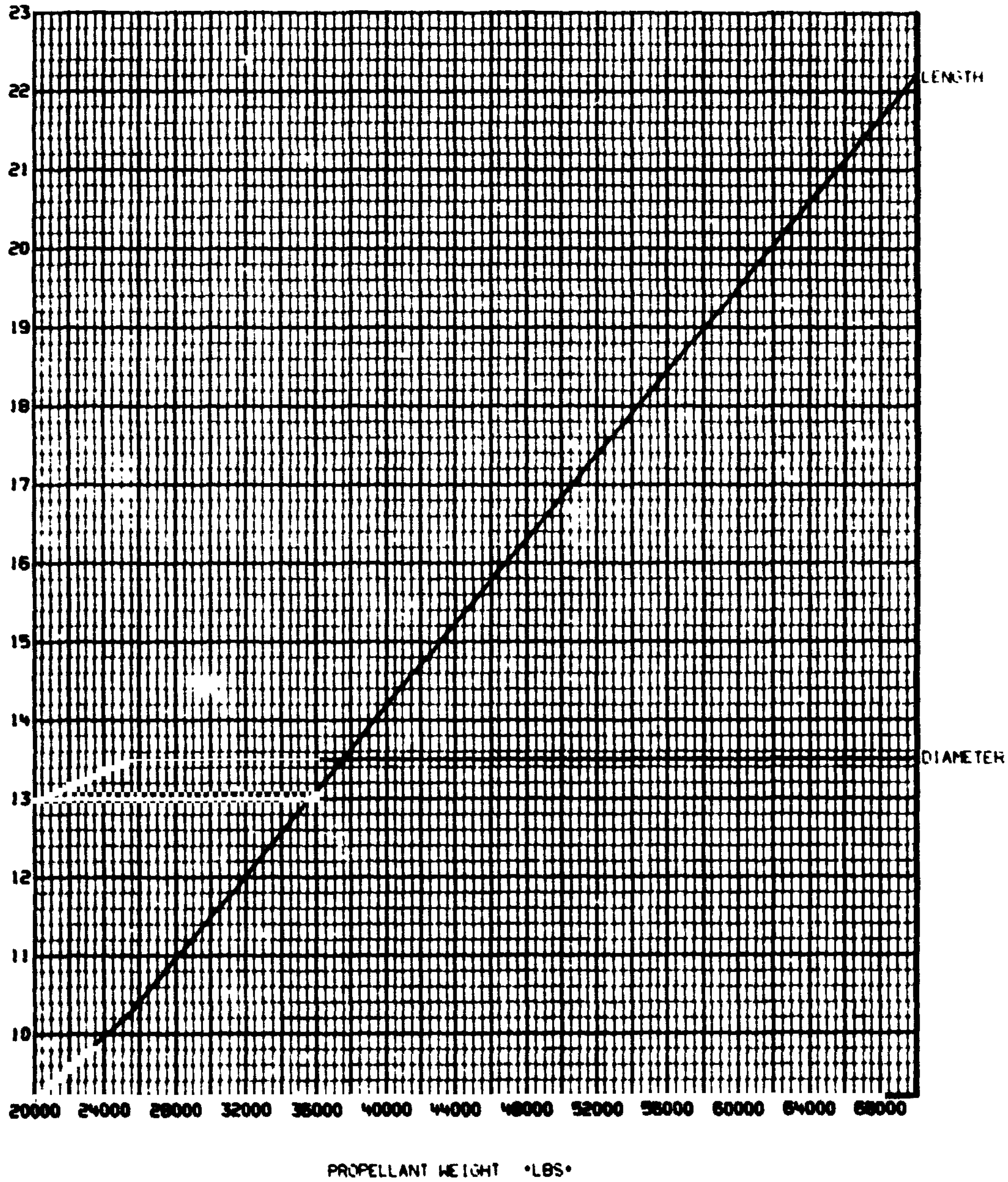


Figure 3-15. Parametric Fuel Tank Sizing Data, LO_2/LH_2 Reusable Tug

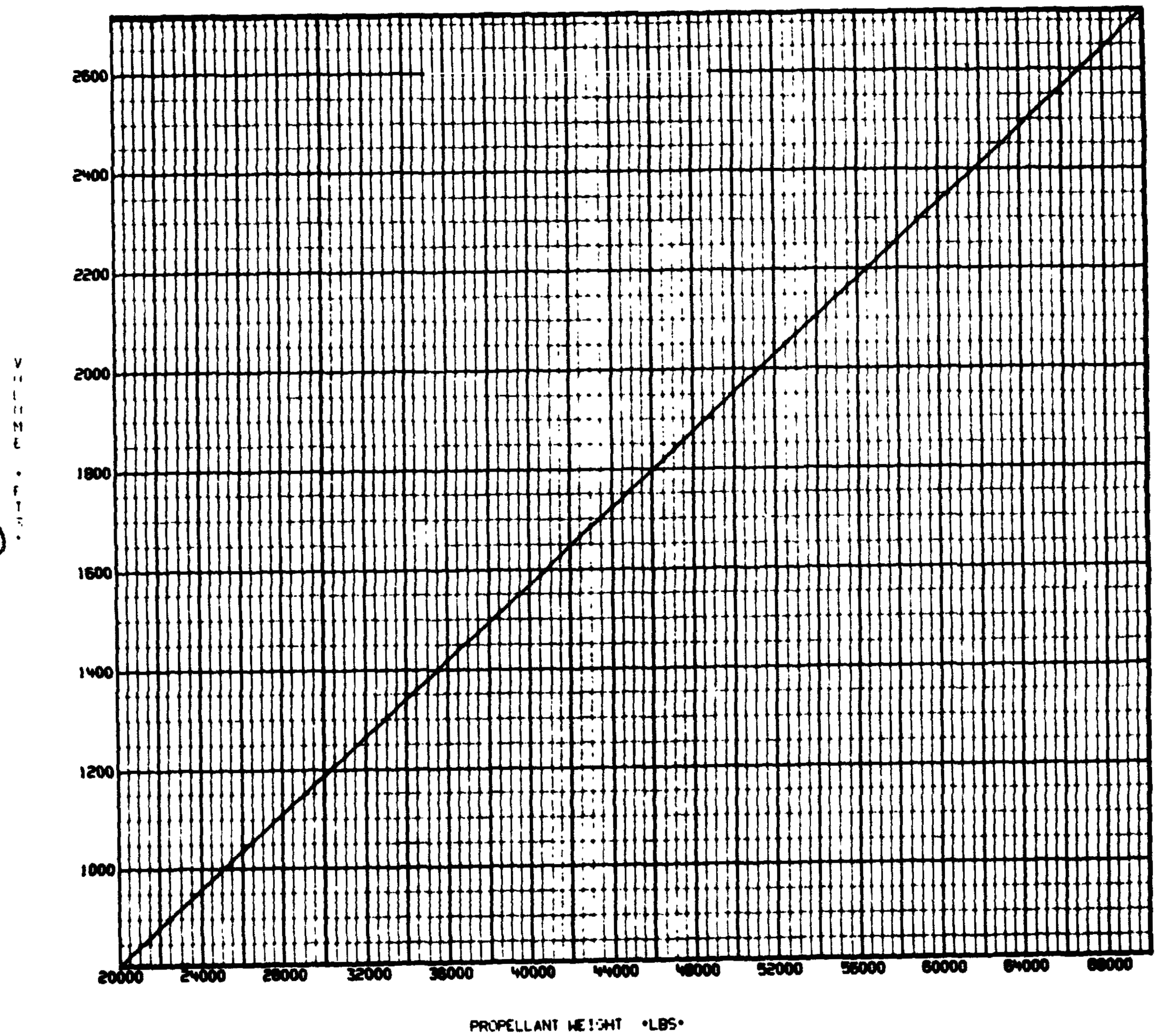


Figure 3-16. Parametric Fuel Tank Volume Data, LO_2/LH_2 Reusable Tug

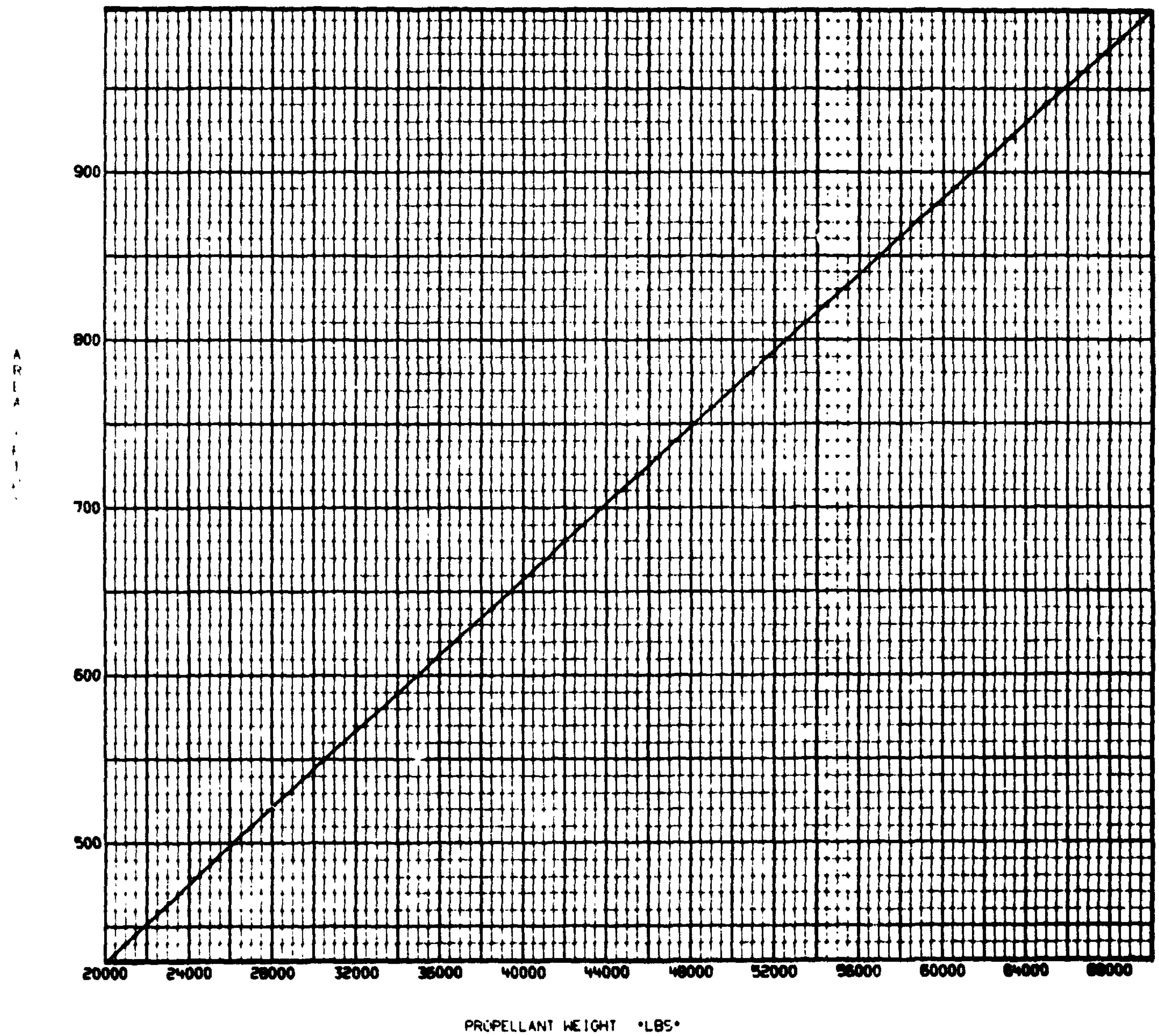


Figure 3-17. Parametric Fuel Tank Area Data, LO_2/LH_2 Reusable Tug

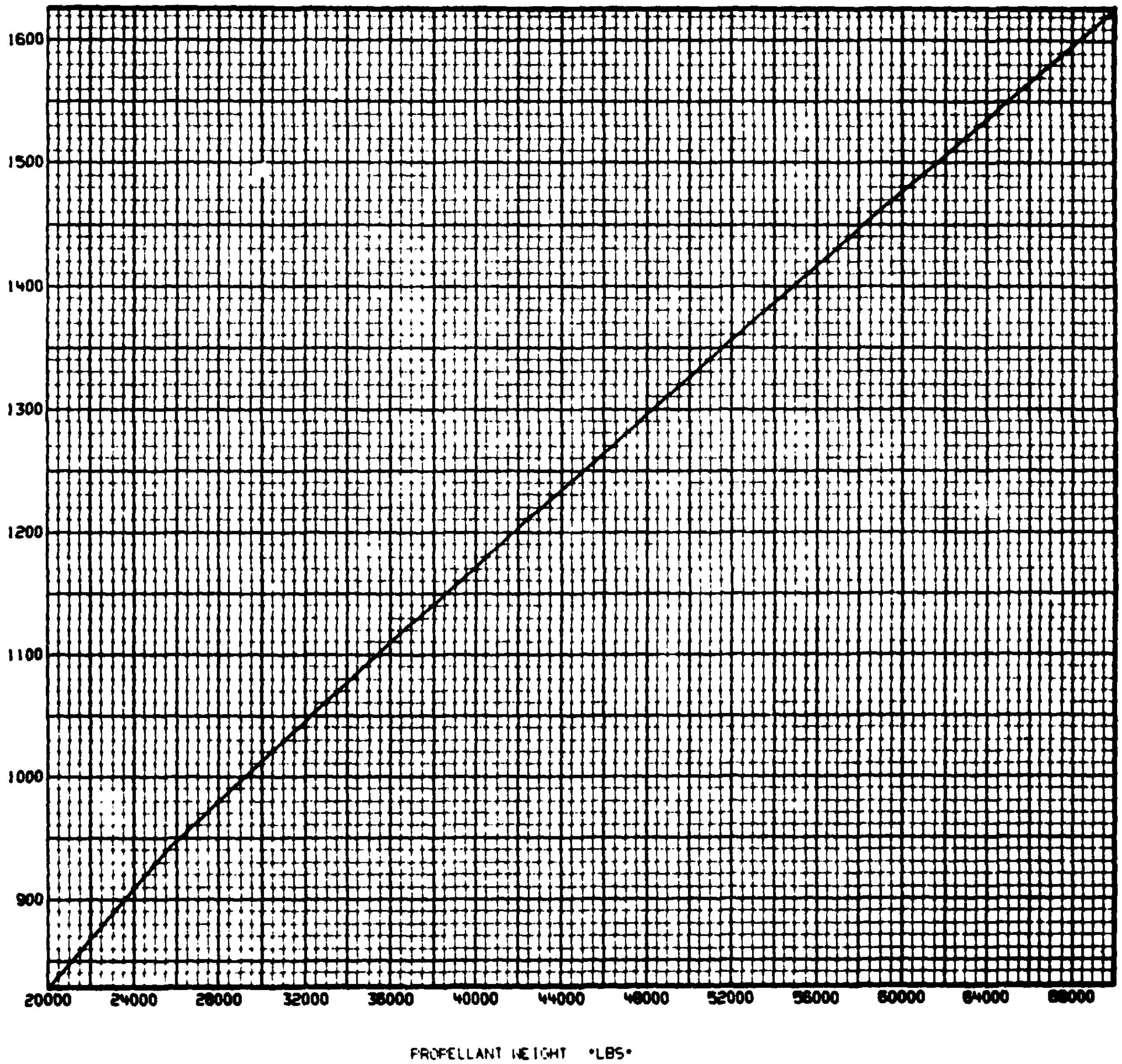


Figure 3-18. Parametric Exterior Area Data, LO_2/LH_2 Reusable Tug

COST DATA

The second element of the Tug data base consists of the cost data and equations necessary to evaluate the nonrecurring and recurring costs of candidate Space Tugs. The structure of the cost data is consistent with the structure of the design data in that point costing is used for the orbit injection stages and parametric cost estimating relationships (CERs) are used for the reusable Space Tug configurations. A description of the Tug costing methodology and the rationale and justification for the choice of the cost constants is presented in Volume III. Consequently, only representative Tug costs are shown here.

As was the case with the DERs, the reusable Tug CERs are automated into a computer subroutine. These CERs are used to generate Tug RDT&E, investment, and operations expenditures; the cost routine uses as inputs the detailed Tug design characteristics and data on year-by-year Tug flight activity levels. A sample of the parametric cost curves generated with the CERs is presented in Figures 3-19 through 3-27; this information is based on the parametric LO_2/LH_2 ground-based Tug design data presented previously. The individual makeup of each cost element is described in Volume III.

These curves help visualize the relative magnitude of each cost element with respect to the total costs; provide a means to evaluate the magnitude of individual cost elements; and also serve to compare Tug costs among propellant types, operational modes (expendable vs reusable), and stage propellant loadings.

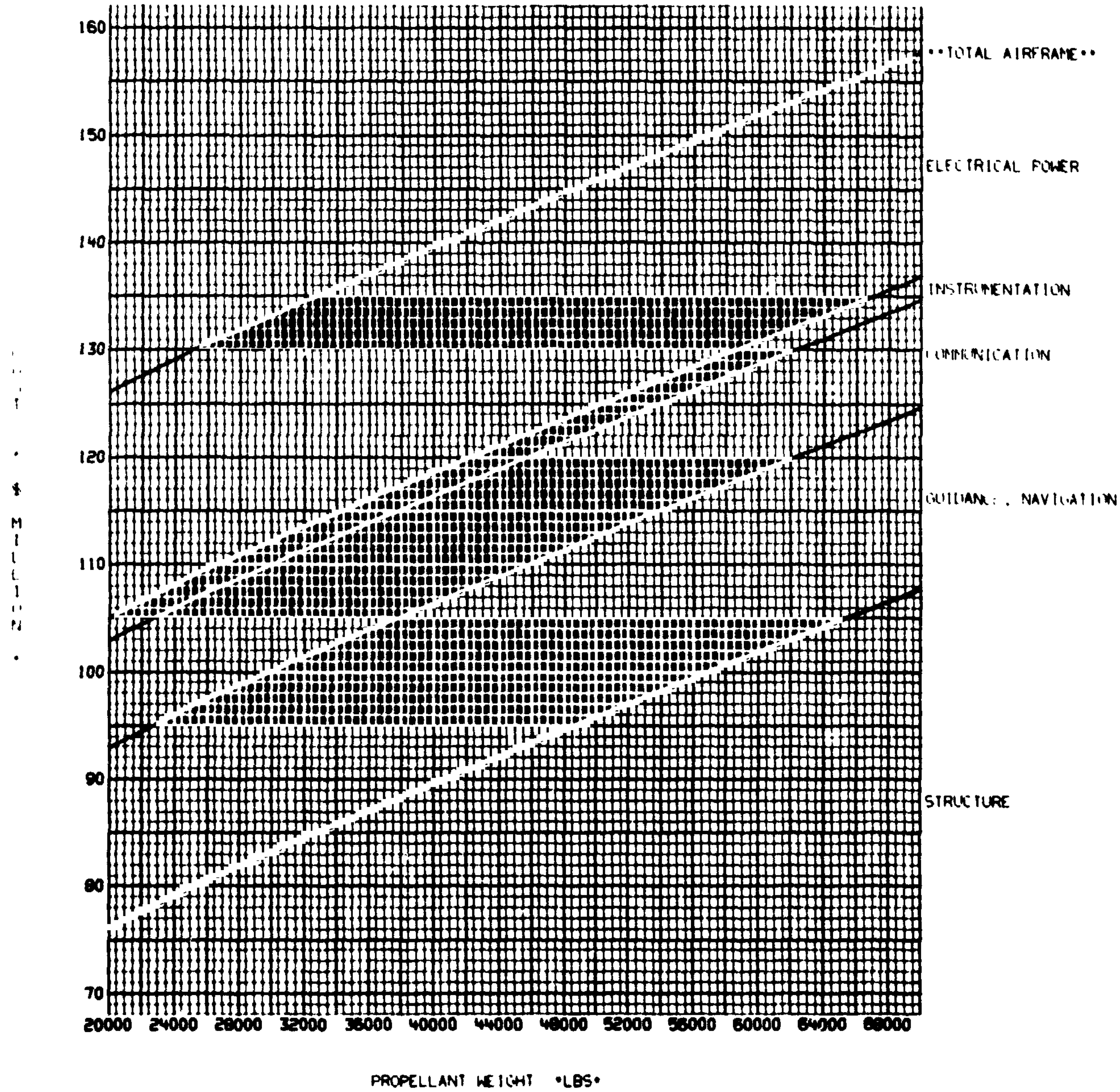


Figure 3-19. Parametric Vehicle RDT&E Costs, Reusable LO_2/LH_2 Tug

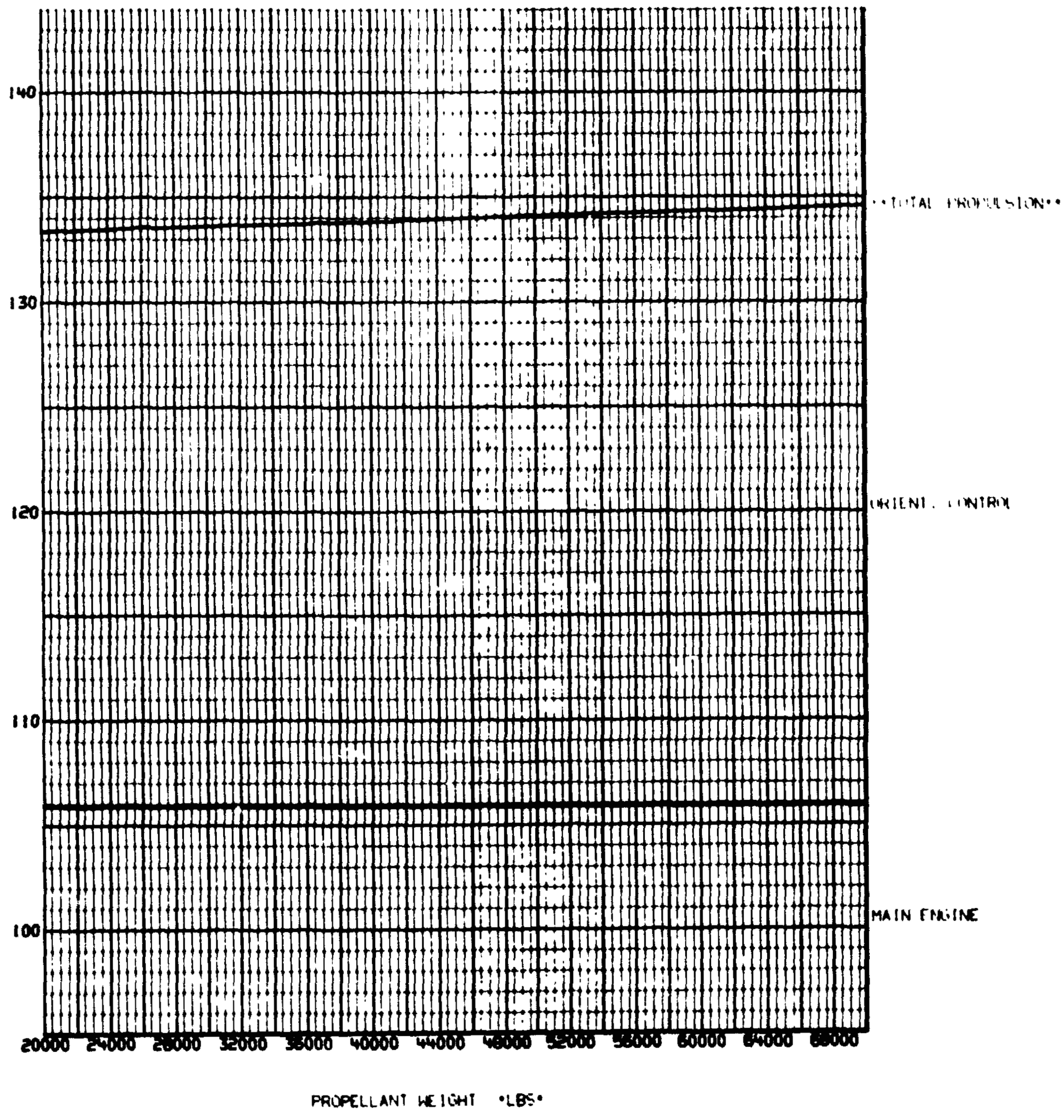


Figure 3-20. Parametric Propulsion RDT&E Costs, Reusable LO_2/LH_2 Tug

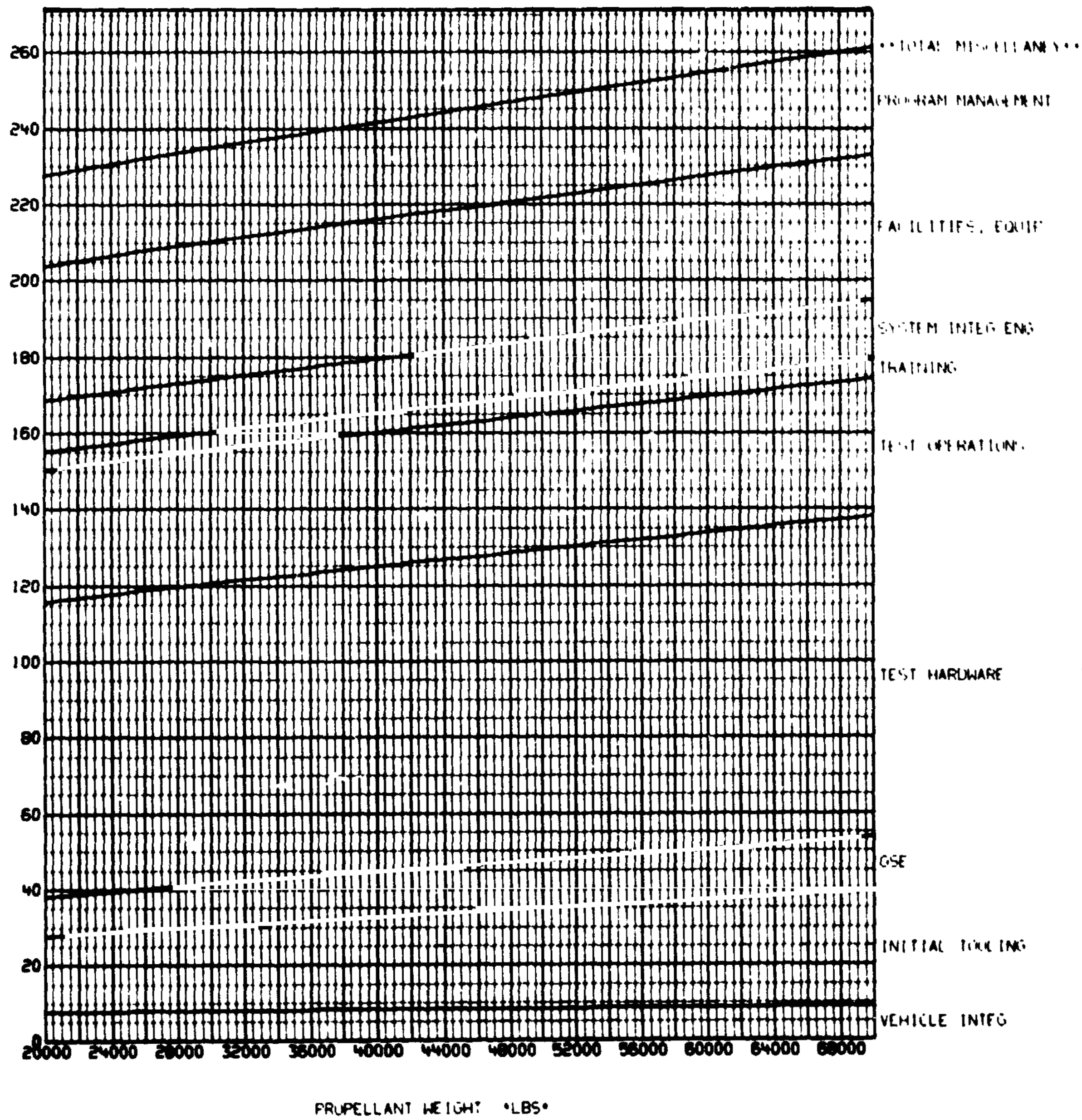


Figure 3-21. Parametric Floating-Item (Miscellaneous) RDT&E Costs, Reusable LO_2/LH_2 Tug

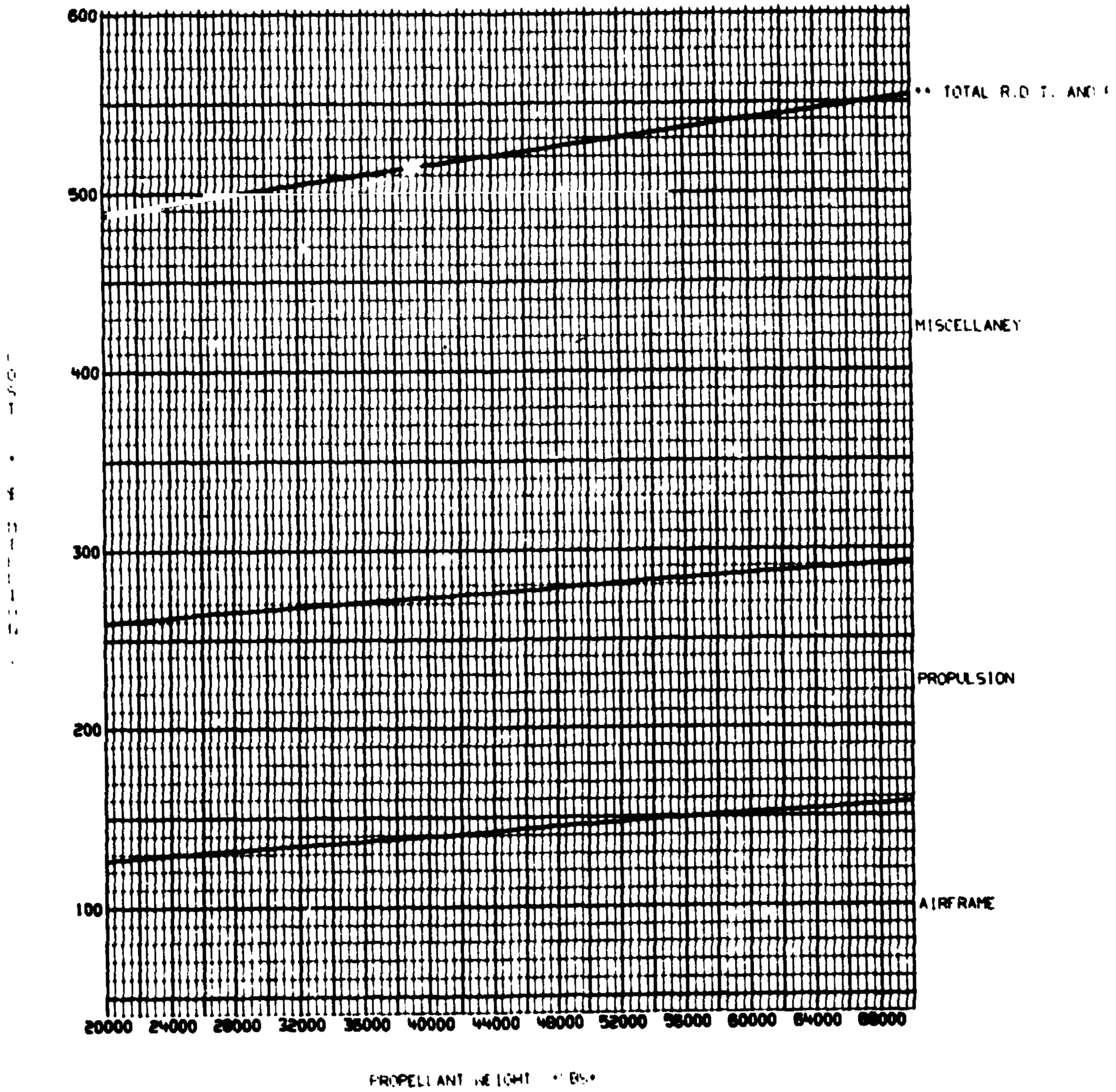


Figure 3-22. Parametric Total RDT&E Costs, Reusable LO_2/LH_2 Tug

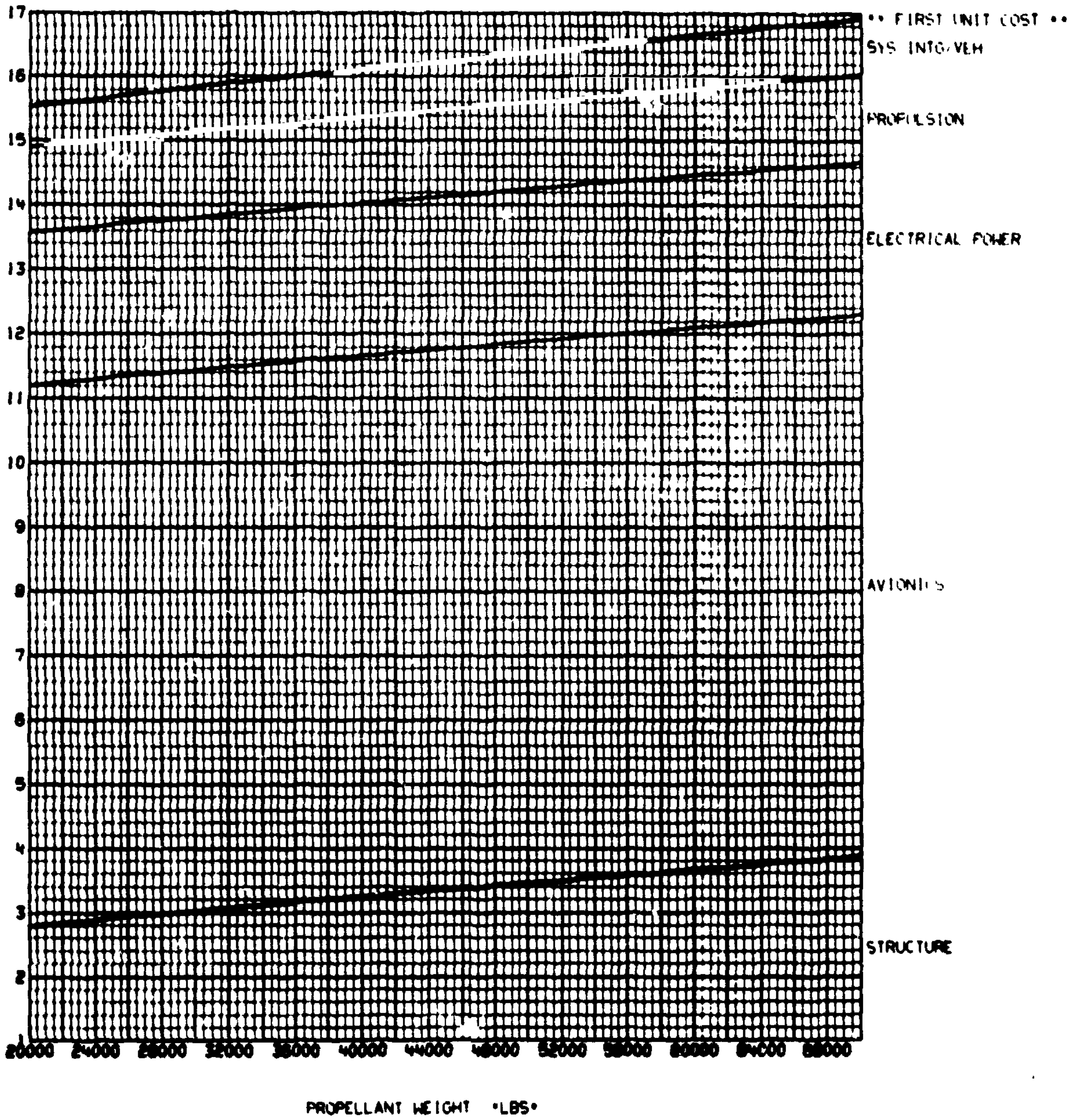


Figure 3-23. Parametric First-Unit Costs, Reusable LO_2/LH_2 Tug

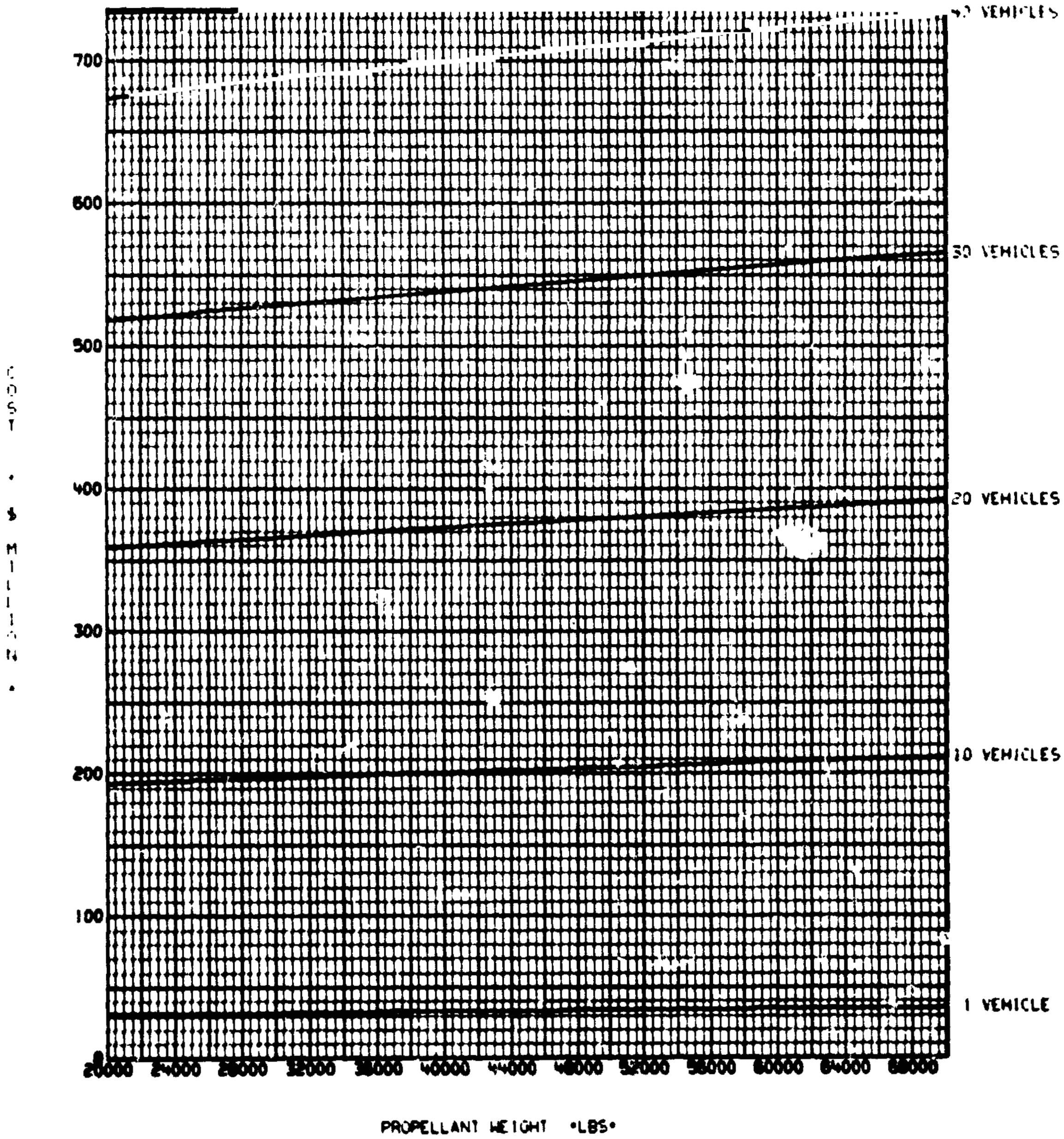


Figure 3-24. Parametric Fleet Investment Costs, Reusable LO_2/LH_2 Tug

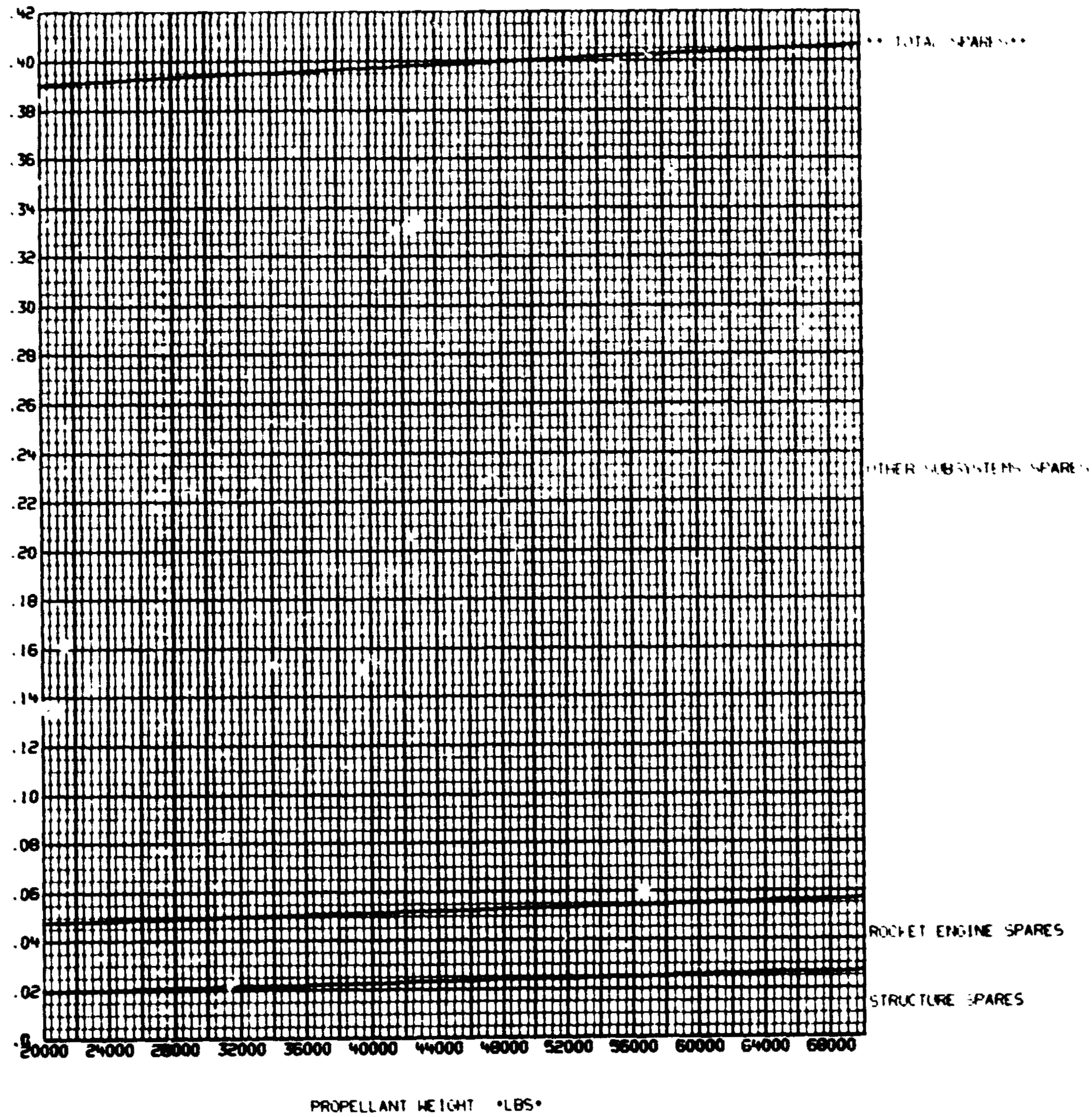


Figure 3-25. Parametric Operational-Phase Spares Cost, Reusable LO_2/LH_2 Tug

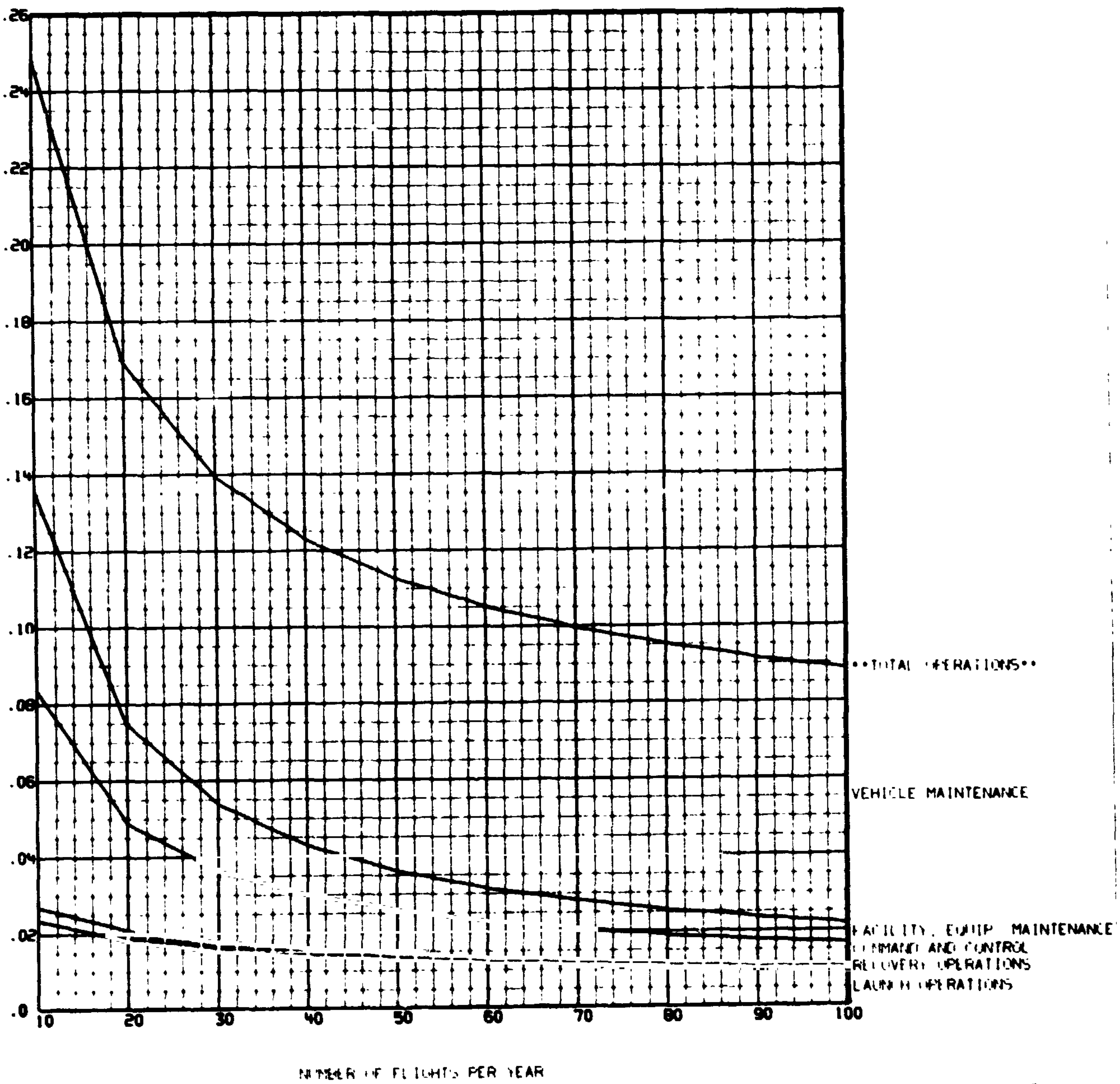


Figure 3-26. Parametric Operations Cost (Activity Level Dependent), LO_2/LH_2 Reusable Tug

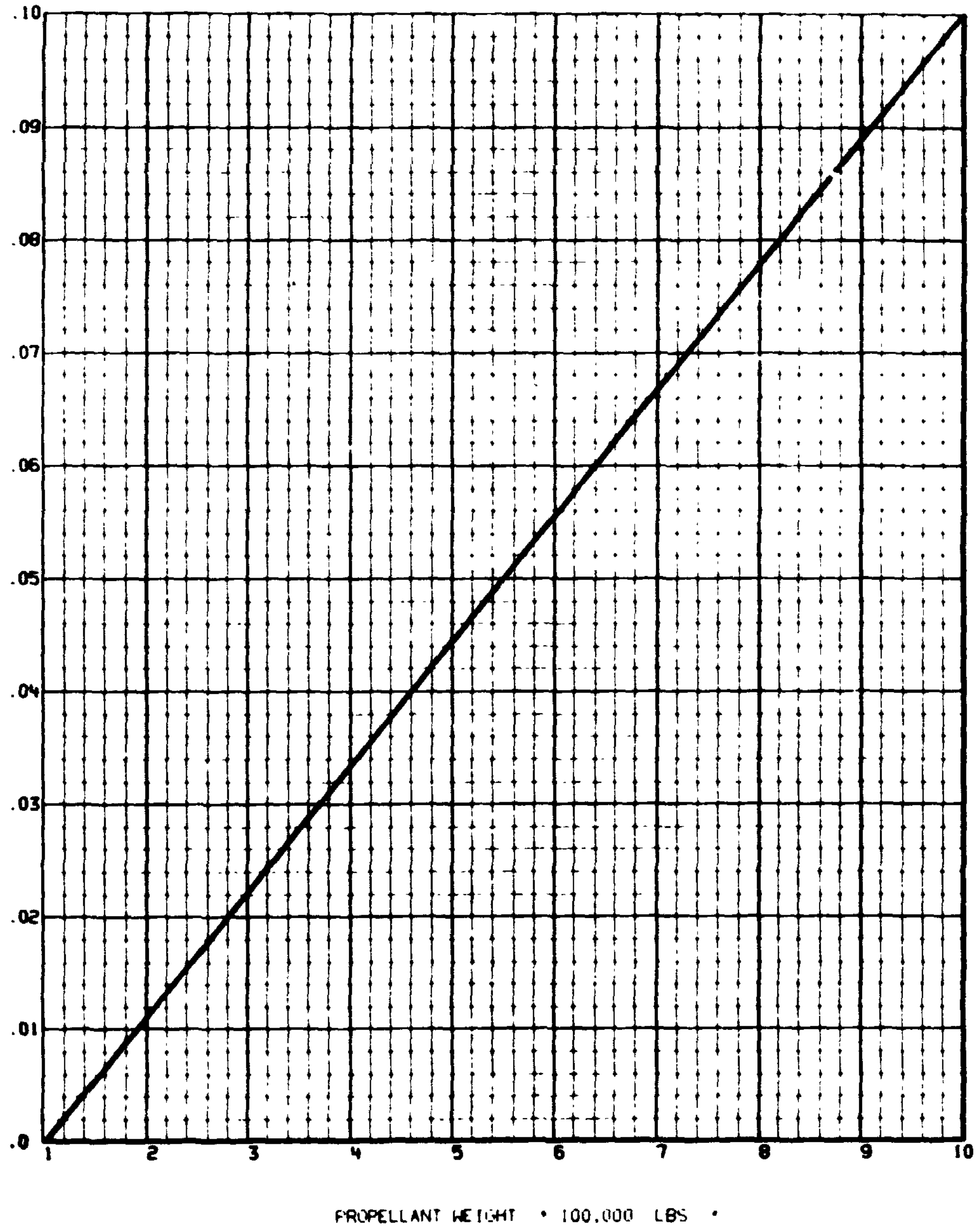


Figure 3-27. Parametric Propellant Cost, LO_2/LH_2 Tugs

PERFORMANCE EQUATIONS

The third element of the data base consists of the performance equations necessary to size the candidate Tugs and evaluate their performance characteristics. The equations used for sizing the reusable Space Tug configurations are presented in Table 3-6. Application of these equations requires a detailed ΔV schedule along with a designation of the type of propulsion system assigned to each maneuver (main or RCS engines). Given a specific set of ignition weight constraints, operational modes, propulsion characteristics, and inert weights, the performance routine calculates Tug propellant weight (both main and RCS propulsion systems) and payload capability. An example of the output format from this analysis is presented in Table 3-7 for a reusable LO_2/LH_2 Tug constrained to an ignition weight of 65,000 lb (including payload). The detailed mission profile used in this stage sizing analysis is representative of a synchronous equatorial payload placement with a reusable Tug. The interface between these equations and the design equations is discussed in Chapter 4.

The equations necessary to access the performance characteristics of a defined Space Tug are presented in Table 3-8. These equations are a function of the Tug operational mode, inert weight, specific impulse, and propellant loading. The equations are automated into a computer subroutine and are combined with a computer plot package. This subroutine can be employed to generate performance characteristics for the defined Space Tugs across the ΔV spectrum. A representative set of curves generated with this routine is presented in Figures 3-28 through 3-31 for a single-stage LO_2/LH_2 Tug with a propellant load of 50,158 lb. There is one curve for each flight mode. This routine also has the capability of evaluating the sensitivity of the constrained and unconstrained payload capability to changes in:

- Tug specific impulse
- Impulse velocity requirements
- Tug inert weight
- Tug propellant weight
- Ignition weight constraint
- Ratio of payload delivered to payload delivered plus payload returned

For the candidate Tugs considered in this study, the performance characteristics and their sensitivities are presented in the Appendix to Volume II.

Table 3-6. EQUATIONS FOR SIZING REUSABLE SPACE TUGS

Let

N = Number of stage maneuvers

μ_i = Mass fraction of the i^{th} maneuver

W_I = $e^{\Delta V i/g\, I SP}$

ΔV_i = Velocity impulse of the i^{th} maneuver

I_{SP_i} = Specific impulse of the propulsion system used during the i^{th} maneuver

W = Weight

W_{ign} = Ignition weight constraint value

W_{D_i} = Weight delivered after the i^{th} event

W_{P_i} = Propellant weight expended during the i^{th} maneuver

W_{R_i} = Weight retrieved after the i^{th} event

W_{O_i} = Ignition weight of the i^{th} maneuver

T = The event number prior to the target

Then

$$W_{O_1} = W_{ign}$$

$$W_{O_i} = W_{O_{i-1}} - W_{P_{i-1}} - W_{D_{i-1}} + W_{R_{i-1}}$$

$$W_{P_i} = (\mu_i - 1)\, W_{O_i}/\mu_i$$

Given ΔV_i, I_{SP_i}, $W_{D_T}\Big/(W_{D_T} + W_{R_T})$, W_{ign}, and the inert weight functions $(W_I + f(W_P))$ these equations are solved iteratively for W_{D_T}, W_{R_T}, and $\sum_{i=1}^{N} W_{P_i}$

Table 3-7. TYPICAL PERFORMANCE CALCULATION OUTPUT

LO2/LH2 ADVANCED TUG DESIGN CONCEPT

SYNCHRONOUS EQUATORIAL MISSION
INITIAL CONDITIONS 100 NM CIRC 28.3 DEG INC EARTH ORBIT
TARGET CONDITIONS 19330 NM CIRC 0 DEG INC EARTH ORBIT
FINAL CONDITIONS 115 NM CIRC 28.3 DEG INC EARTH ORBIT

COMMENTS
OUTBOUND FLIGHT PROFILE HOHMANN XSFER OPT INC SPLIT
RETURN FLIGHT PROFILE HOHMANN XSFER OPT INC SPLIT
STAY TIME AT TARGET 4 HOURS
PAYLOAD LENGTH .0 FT
PAYLOAD DELIVERED TO TARGET 8229. PAYLOAD DENSITY .000 LB/FT3 BASED ON D4
PAYLOAD RETURNED TO FINAL CON 0. PAYLOAD DENSITY .000 LB/FT3 BASED ON D4
IMPULSE PROPELLANT 50158. RCS PROPELLANT 402.510
WET INERT WEIGHT 8210. MISSION SEQUENCE

CONDITIONS	EVENT	TIME DY:HR:MIN	DELTA V FPS	ENGINE TYPE	WEIGHT LBS	DELTA WT LBS	IMP PROP REM LBS
INITIAL	PHASING ORBIT INJECTION	01 01 .0	7932.	MAIN	65000.0	24979.6	50158.2
		01 0110.3			38020.4	.0	23178.6
	TRANSFER ORBIT INJECTION	01 9118.3	260.	MAIN	38020.4	662.5	23178.6
		01 9118.6			37357.9	.0	22516.1
	MIDCOURSE	01101 .6	10.	RCS	37357.9	42.4	22516.1
		01101 2.5			37315.6	.0	22516.1
	SYN EQ INJECTION	0114131.5	5867.	MAIN	37315.6	12218.4	22516.1
		0114136.2			25097.2	.0	10297.8
	PROP RESERVES	0114136.2	140.	MAIN	25097.2	236.4	10297.8
		0114136.3			24860.8	.0	10061.3
	RENDEZVOUS, DOCKING	0114136.3			24860.8		10061.3
TARGET 1			100.	RCS		280.6	
		0114149.1			24580.2	8229.3	10061.3
	TRANSFER ORBIT INJECTION	0118149.1	5850.	MAIN	16350.9	5341.2	10061.3
		0118151.2			11009.7	.0	4720.1
	PHASING ORBIT INJECTION	11 01 7.2	5405.	MAIN	11009.7	3370.0	4720.1
		11 01 8.5			7639.7	.0	1350.1
	MIDCOURSE	11 0112.5	10.	RCS	7639.7	8.7	1350.1
		11 0112.9			7631.0	.0	1350.1
	INJECTION INTO 115 CIRC	11 1116.9	2740.	MAIN	7631.0	1290.4	1350.1
		11 1117.3			6340.6		59.7

Table 3-7. (Continued)

	PROP RESERVES	1: 1:17.3			6340.6	.0	59.7
			140.	MAIN		59.7	
		1: 1:17.4			6280.9		-.0
	RENDEZVOUS,DOCKING	1: 1:17.4			6280.9	.0	-.0
FINAL			100.	RCS		70.9	
		1: 1:20.6			6210.0		-.0

Table 3-8. EQUATIONS FOR REUSABLE TUG PERFORMANCE

Equation Description	Single Stage Performance	
	Ignition Weight Unconstrained	Ignition Weight Constrained
Roundtrip Capability	$\lvert W_P - W_I(\mu_1\mu_2 - 1)\rvert / (\mu_1\mu_2 - 1)$	$W_O/\mu_1\mu_2 - W_I$
Dedicated Retrieval	$\lvert W_P - W_I(\mu_1\mu_2 - 1)\rvert / (\mu_1\mu_2 - \mu_1)$	$W_O/\ \mu_1(\mu_2 - 1)\ - W_I\mu_2/(\mu_2 - 1)$
Expendable P/L Reusable Tug	$\lvert W_P - W_I(\mu_1\mu_2 - 1)\rvert / (\mu_1 - 1)$	$W_O/\mu_1\ - W_I\mu_2$
Expendable P/L Reusable Tug	$W_P/(\mu_1 - 1) - W_I$	$W_O/\mu_1 - W_I$

For Tandem Stage Performance the following two equations are solved iteratively for both constrained and unconstrained ignition weight

$$1.\ \mu_{11} = \frac{W_{I_1} + W_{I_2} + W_{P_1} + W_{P_2} + W_D}{W_I\mu_{11} + W_{I_2} + W_{P_2} + W_D}$$

$$2.\ \mu_{21} = \frac{W_{I_2} + W_{P_2} + W_D}{W_{I_2} + (W_{I_2} + W_R)(\mu_{22} - 1) + W_D}$$

Where: W_I = inert weight
W_P = propellant weight
W_D = payload weight delivered
W_R = payload weight retrieved
W_O = ignition weight constraint

μ_i = mass fraction of the ith maneuver $i = 1, 2$
μ_{ij} = mass fraction of the jth burn of the ith stage $i = 1, 2 \quad j = 1, 2$

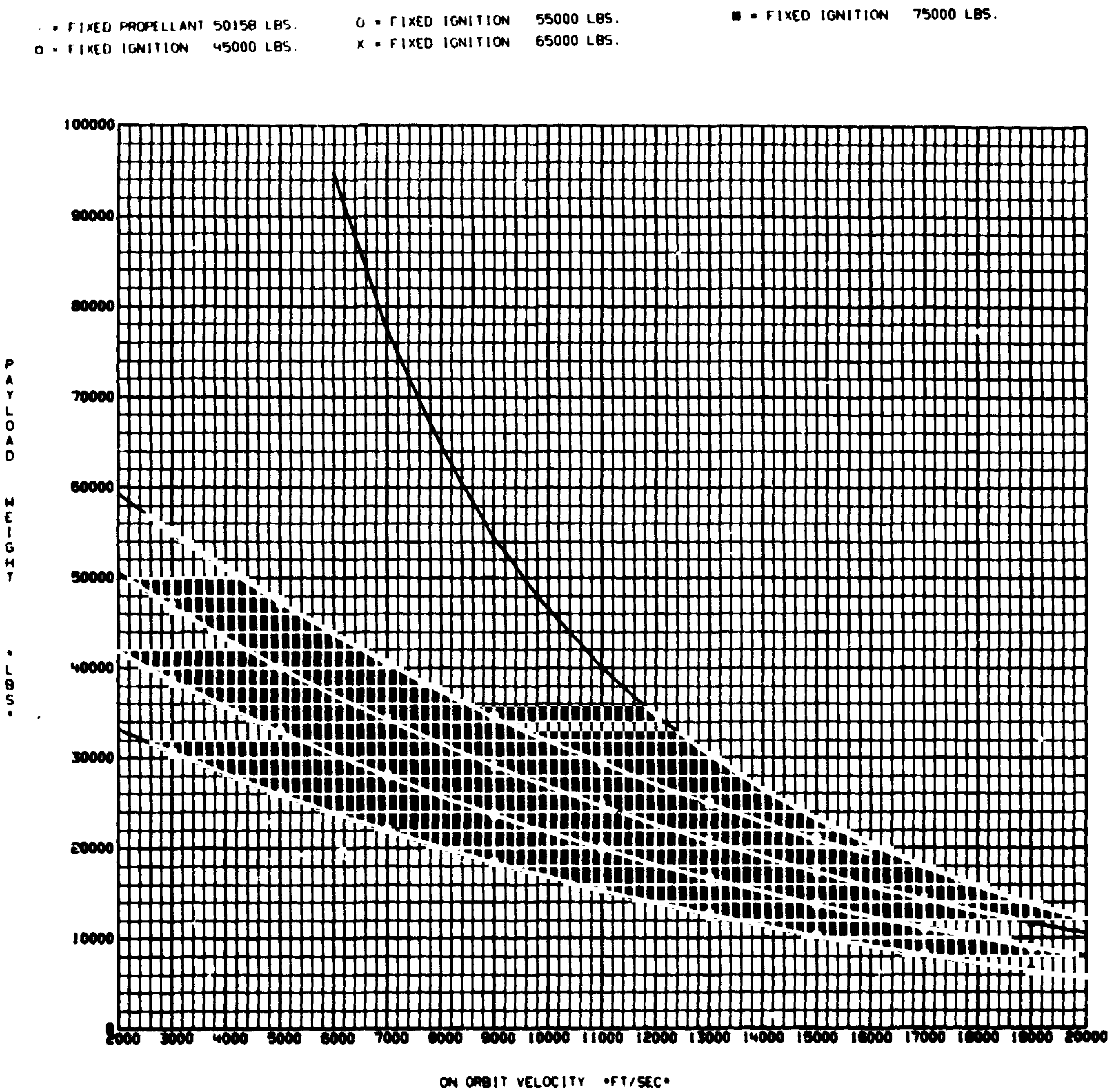


Figure 3-28. Typical LO_2/LH_2 Tug Performance Curves, Mode 4 (All-Expendable)

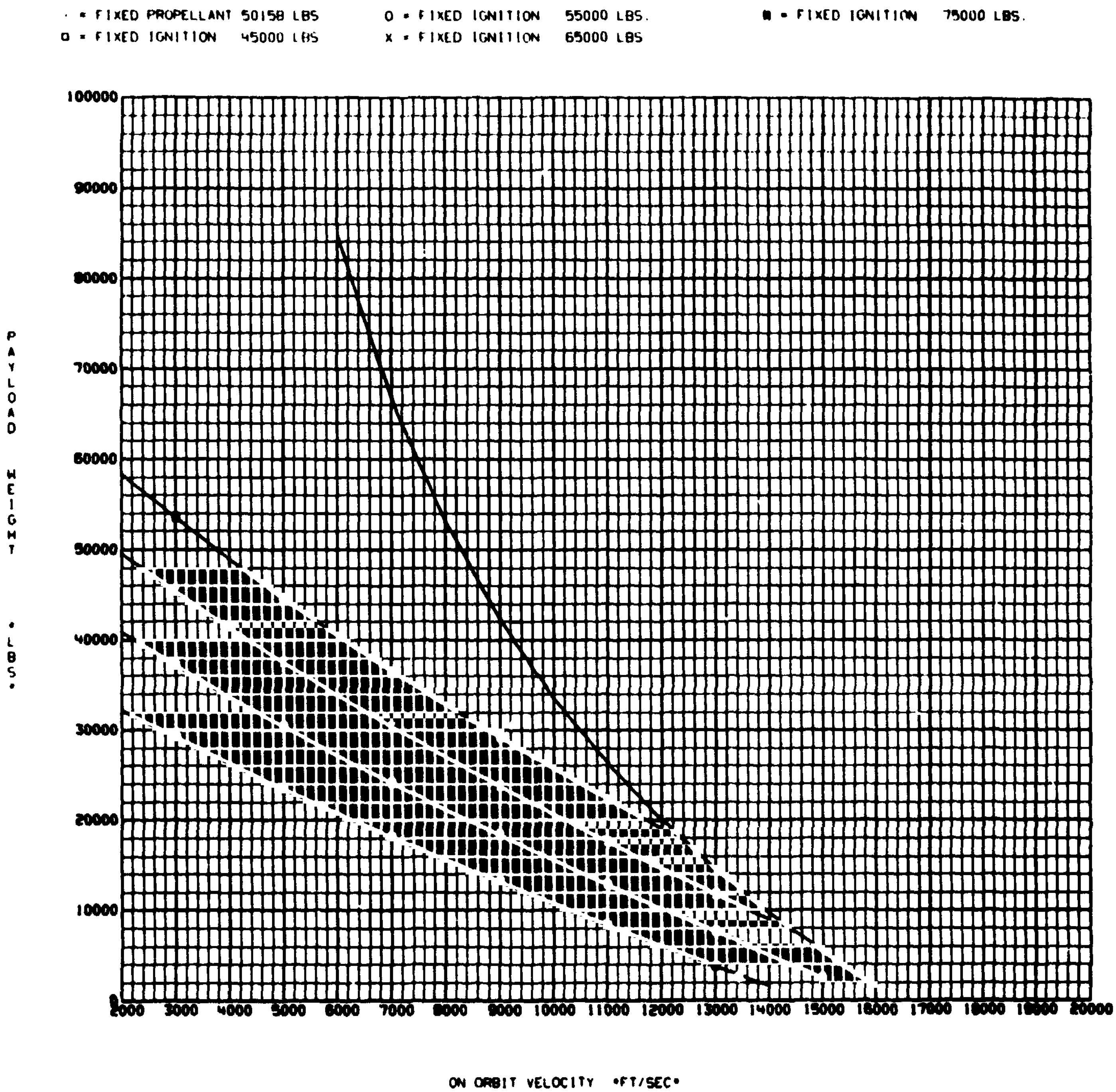


Figure 3-29. Typical LO_2/LH_2 Performance Curves, Mode 3
(Expendable Payload, Reusable Tug)

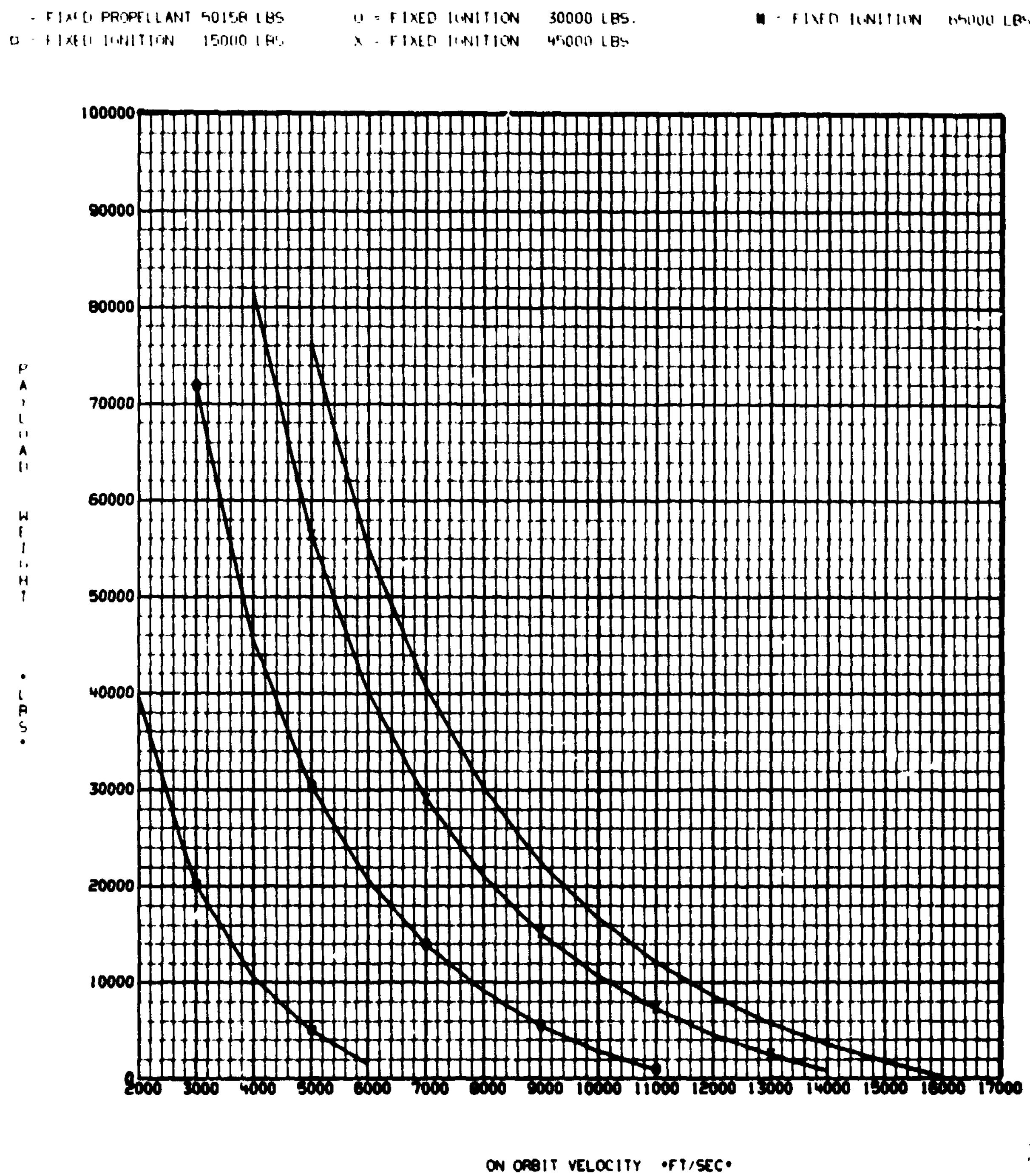


Figure 3-30. Typical LO_2/LH_2 Tug Performance Curves, Mode 2 (Reusable Tug, Retrieval Only)

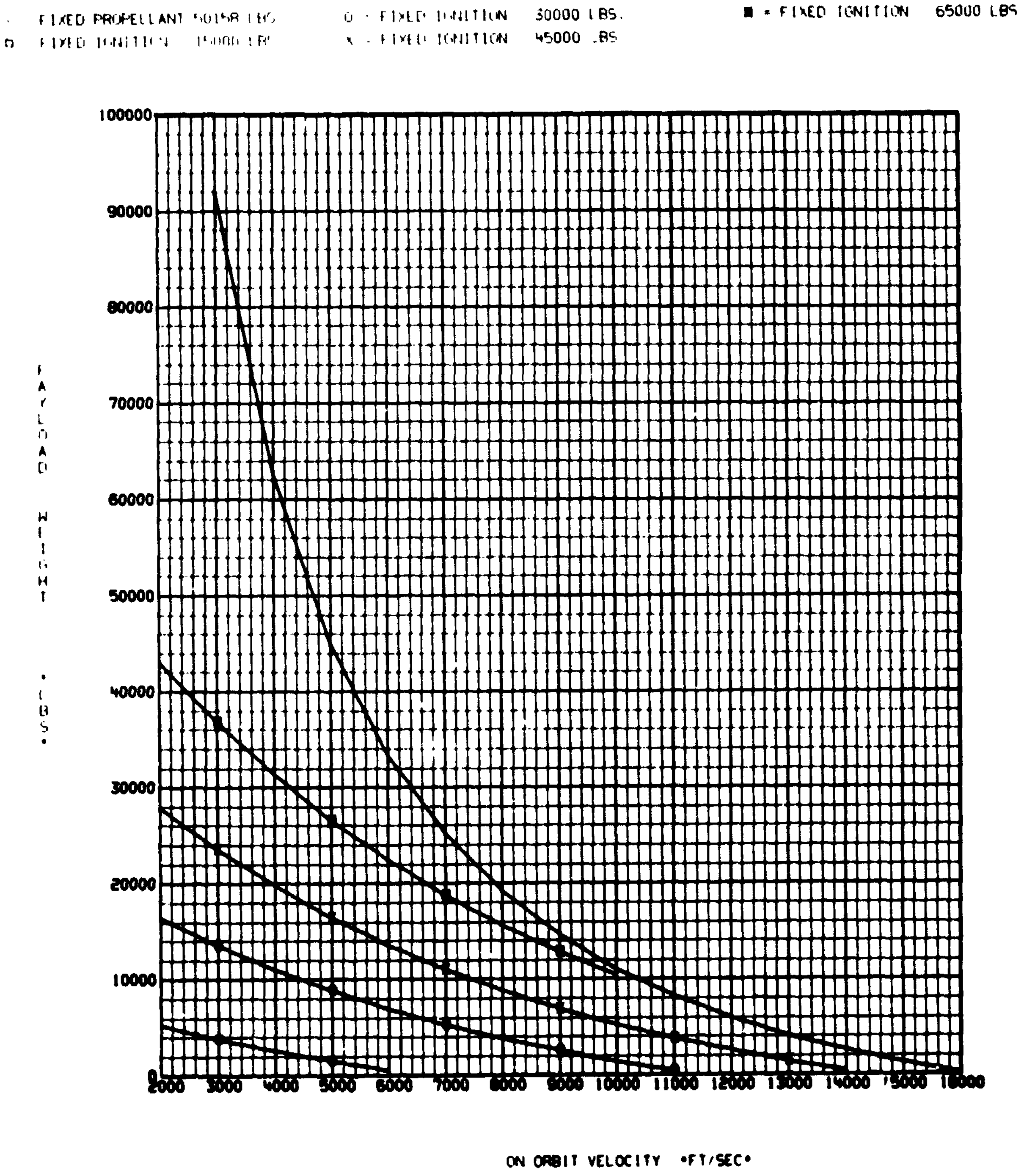


Figure 3-31. Typical LO_2/LH_2 Tug Performance Curves, Mode 1 (Roundtrip Delivery of Equal Weight Payloads)

PAYLOAD DATA

The basic mission model, the schedule of cost inducing events, the payload cost elements, and all other fixed data pertaining to the mission model (against which candidate Tugs are evaluated) are all assembled into a detailed and comprehensive data file that makes up the fourth element in the data base. A printout of these data for one typical program, Fleming Mission No. 28 (Application Technology Satellite), is shown in Figure 3-32. For every program in the mission model, one such data sheet was prepared. Each sheet contains a full description of the baseline and low-cost weights and costs; sizes; power requirements; flight schedules; and mission definitions for the given payload.

The baseline and low-cost cost estimates shown for these payloads were derived by Lockheed using a parametric cost methodology. Historical cost estimating relationships were applied at the subsystem level using the subsystem weight breakdowns. The costs so derived were cross checked, where possible, with Aerospace Corporation estimates for the same payloads (derived on the Shuttle Economics study). This cross checking showed favorable agreement between the Lockheed and Aerospace payload cost estimates.

A similar data sheet for each payload in the mission model is provided in Volume III.

SPACE SHUTTLE DEFINITION

The two-stage, fully reusable Space Shuttle configuration was assumed for this study. A groundrule in the study was that the Shuttle delivered all Tugs and payloads to a 100 nm orbit and that all Tug operations began and ended (if reusable) at this orbital altitude. Figure 3-33 shows the Space Shuttle payload capability to the 100 nm orbital altitude as a function of orbit inclination. (Payload capability was provided by NASA/MSFC.) It was also assumed for this study that the Shuttle cargo bay would be sized to 15 feet by 60 feet and that a $5 million user fee would be applied to each flight of the Shuttle. No other Tug/payload interfaces with the Shuttle were specified.

MISSION PLANNING NUMBER: 28   SUBFIELD: 0   NAME: APPLIC. TECHNOLOGY SAT.   ** MISSION / PAYLOAD DATA **
MISSION CODE NUMBER: NCN-1   ** (BASELINE & LOW COST) **

INCLINATION: .00 DEGREES
DV: 14108. FT/SEC
LIFE: 5.0 YEARS
NUMBER OF ACTIVE PAYLOADS ON ORBIT: 2

ORBIT: SYNC.H(P) / SYNC.H(A)
AVERAGE POWER: 6000. WATTS
SIZE: DIAMETER 15.0 FT. LENGTH 21.0 FT.
DENSITY: 2.2 LBS/FT3

ACCEPTABLE MISSION MODES:
** YES** RETRIEVABLE PAYLOAD (MODE 1)   ** YES** EXPENDABLE PAYLOAD (MODE 3)
** YES** RETRIEVABLE PAYLOAD (MODE 2)   ** YES** EXPENDABLE PAYLOAD (MODE 4)

LAUNCH SCHEDULE: ** | **YEAR	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97
NUMBER OF LAUNCHES	1		1		1	1		1		1	1								
NEW UNITS (EXPENDABLE)	1		1		1	1		1		1	1								
NUMBER OF RETRIEVALS						1		1		1									
NEW UNITS - N-R INV (REUSEABLE)	1		1		1														
NEW UNITS - REC INV (REUSEABLE)						1													
EXPERIMENT R&D APPLICATION	*				*			*			*								
OPERATION INDEPENDENT COST APPLICATION	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				

** WEIGHTS & COSTS: **	**WEIGHT (LBS)** *B/L*	*L/C*	**R&D COST ($M)** *BASELINE*		*LOW COST* *NO RISK*	*RISK*	**UNIT COST ($M)** *BASELINE*		*LOW COST* *NO RISK*	*RISK*
SUBSYSTEM										
ADAPTER	280.	411.	1.400		.964	.964	.232		.157	.157
EXPERIMENT MISSION EQUIPMENT	1600.	3281.	40.960	(1.29)	34.253	31.855	6.600	(1.35)	5.839	5.397
STRUCTURES AND MECHANISMS	1200.	1823.	16.305	(2.00)	10.800	9.511	1.200		1.013	1.013
ELECTRICAL POWER	2900.	3926.	40.735	(1.73)	29.437	26.511	5.140		4.443	3.721
STABILITY & CONTROL	1000.	1167.	102.000		100.063	86.828	28.900		11.881	10.931
ATTITUDE CONTROL	150.	913.	5.190		4.856	4.371	1.230		1.008	1.008
PROPULSION	0.	0.	.000		.000	.000	.000		.000	.000
TRACKING & TELEMETRY	400.	440.	78.707		62.475	56.228	6.200		5.221	4.751
ENVIRONMENTAL CONTROL	300.	300.	14.000		14.000	12.600	2.750		2.750	2.750
EXPENDABLE PROP. & GASSES	400.	820.	.000		.000	.000	.800		.000	.000
** TOTAL **	8230.	12087.	316.340		257.777	228.860	43.910		32.349	29.729

MIN. INERT WT. EXPENDABLE P/L 7830.
MIN. TOTAL WT. EXPENDABLE P/L 8230.

REFURB. TOTAL WT. REUSEABLE P/L 1527.
MIN. PROPELLANT WT. REUSEABLE P/L 474.
MIN. INERT WT. REUSEABLE P/L 9283.
MIN. TOTAL WT. REUSEABLE P/L 9757.

REFURB. INERT WT. 1453.
REFURB. PROP. WT. 74.
REFURB. L/C S/S WT. 1492.
L/C SUBSYSTEMS WT. 12587.
FIXED SUBSYSTEMS WT. 300.
FACTOR: (L/C-B/L-REF(L/C)) = 3165.16
RATIO: INERT WT./TOTAL WT. = .95140

RISK SAVINGS ($M)	*REUSE.*	*EXPEND.*
R&D EXPERIMENT	2.3977	.9591
TOTAL R&D	28.9084	11.5633
TOTAL UNIT	2.6201	1.0486

R&D PHASE: 6.3 YEARS   R&D SPREAD 50% TIME AT .28 COST
NEW EXPERIMENT R&D: YES   (EVERY 2 LAUNCHES)

OPERATING COST: DEPENDENT $ 5.400 MILLION/LAUNCH, INDEPENDENT $ 11.700 MILLION/YEAR

FIXED PORTION INITIAL INVESTMENT: $ .000 MILLION
INVESTMENT PHASE: 3.00 YEARS   INVESTMENT SPREAD: 50% TIME AT .50 COST   P/L COST CONFIDENCE: FAIR

PERIGEE ALTITUDE: 19323.00 N.M.   APOGEE ALTITUDE: 19323.00 N.M.
INITIAL ORBIT INCLINATION: 28.50 DEGREES   TUG MISSION DURATION: .00 HOURS

% RETRIEVED PAYLOAD WEIGHT: IN MODE 1 = 100.% AND IN MODE 2 = 100.%

Figure 3-32. Mission/Payload Data

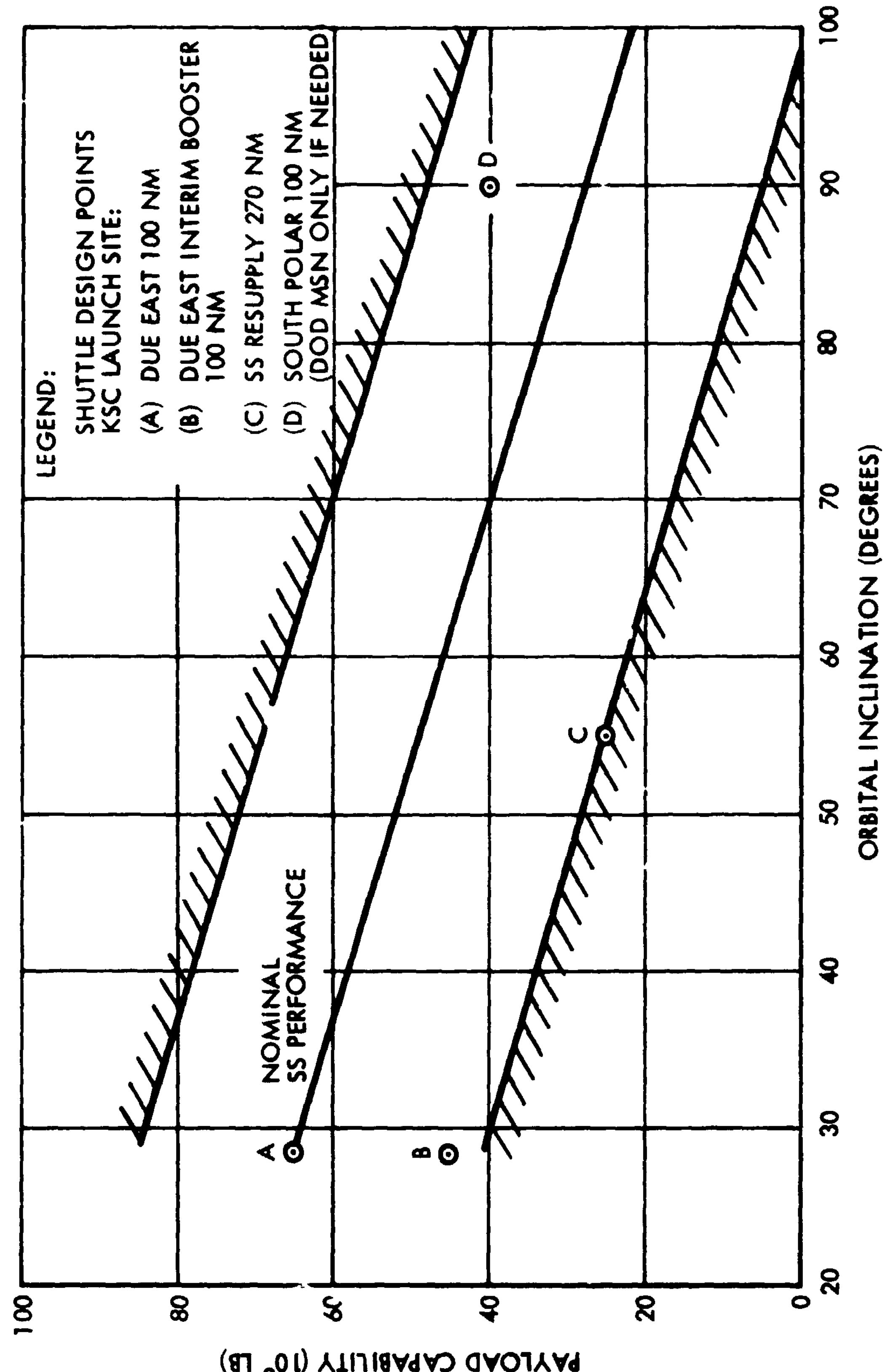


Figure 3-33. Shuttle Performance Spectrum, Two Stage Reusable (100 nm)

TUG SYNTHESIS AND DEFINITION

By interrelating the design, cost, and performance components of the data base, the defining characteristics were generated for each of the candidate Tugs considered in this study. A summary of these characteristics is presented in Tables 3-9 and 3-10. The design and cost data in Table 3-9 reflect the following trends:

- The configurations using earth-storable propellants (Agena and Large Tank Agena) and space-storables ($FLOX/CH_4$) are appreciably shorter and lighter than cryogenic Tugs of equal propellant loading.
- The RDT&E costs of orbit injection stages (which include modifications for Shuttle compatibility) are low compared to the reusable Tugs.
- The RDT&E costs of reusable Space Tugs, which are calculated on a parametric basis, reflect relatively small differences between propellant combinations. This is because the weights of the fluorine-based systems are lighter than the LO_2/LH_2 configurations and the weight differences offset the complexity factors assigned the fluorine-propellant Tugs.
- Unit production costs for the orbital injection stages are low compared to the reusable Tugs; however, the unit cost of the reusable vehicles, when used in an expendable mode, drops by as much as one-half when the reuse hardware is deleted.

Comparative Space Tug performance data for payload delivery to, and retrieval from, synchronous equatorial orbit are presented in Table 3-10. This data is based on payload delivery from a 100 nm circular orbit inclined at 28.5 degrees and a return to the same conditions for these operational modes where a reusable Tug is used. Definition of the four flight modes referenced in this table is as follows:

- Mode 1. Roundtrip delivery of equal weight payloads by one Tug
- Mode 2. Retrieval, only, of a payload in one Tug roundtrip flight
- Mode 3. Delivery, only, of a payload in one Tug roundtrip flight
- Mode 4. Delivery of an expendable payload with no Tug return.

Table 3-10 shows that in the Tug/payload round trip mode (Mode 1) the LF_2/LH_2 Tugs attain the maximum capability, followed by the LO_2/LH_2 and $FLOX/CH_4$ concepts. The expendable orbit injection stages have no capability in the reusable Tug modes (Modes 1, 2, and 3). Note that in Mode 4 (all-expendable) most of the Tugs can deliver a payload weight exceeding that of the largest synchronous equatorial spacecraft in the model.

Performance figures shown in Table 3-10 with two values divided by a slash mark represent cases in which the combined weight of the Tug and the payload exceed the Shuttle weight carrying capability. The figure on the left is the theoretical Tug capability unconstrained by the weight limitation, and the figure on the right is the payload capability when constrained to the 65,000 lb due-East shuttle delivery capacity.

Table 3-9. SPACE TUG CHARACTERISTICS

SPACE TUG DESIGNATION	IMPULSE PROP WT (LB)	SPECIFIC IMPULSE (SEC)	VAC THRUST (LB)	WET INERT* WEIGHT (LB)	STAGE LENGTH (FT)	RDT&E COST (MIL $)	1ST UNIT COST** (MIL $)
AGENA	13,400	290.8	16,100	1257	20.6	43.9	2.20***
D-1T CENTAUR	30,000	444	30,000	4488	32.2	61.5	4.75***
G T CENTAUR	45,000	444	30,000	4252 DRY	37.0	65.5	5.25***
LG TANK AGENA	48,800	310	17,100	1853 DRY	23.8	51.5	2.59***
LO_2/LH_2	30,000	460	20,000	5100/4200	28.7	501.7	15.84
LO_2/LH_2	36,300	460	20,000	5450/4560	30.9	509.9	16.01
LO_2/LH_2	43,000	460	20,000	5850/4950	33.1	518.9	16.20
LO_2/LH_2	50,200	460	20,000	6290/5390	35.4	528.2	16.39
LO_2/LH_2	57,700	460	20,000	6760/5860	37.9	538.0	16.59
LO_2/LH_2	50,200	444	15,000	6120/5220	36.1	456.3	16.38
LO_2/LH_2	50,200	470	20,000	6290/5390	35.4	548.2	16.39
$FLOX/CH_4$	44,000	414	20,000	4520/3650	23.8	448.7	14.41
$FLOX/CH_4$	52,000	414	20,000	4980/4100	25.1	469.7	14.58
$FLOX/CH_4$	58,900	414	20,000	5260/4380	25.8	475.2	14.68
LF_2/LH_2	47,800	474.4	20,000	5440/4540	28.1	576.2	16.57
LF_2/LH_2	54,200	[illegible]4	20,000	5720/4830	29.4	582.8	16.71
LF_2/LH_2	60,600	[illegible].4	20,000	6010/5120	30.6	589.4	16.86

* REUSABLE VEHICLE WEIGHT/EXPENDABLE VEHICLE WEIGHT
** RECURRING-PRODUCTION COST, EXCLUDING MISSION-PECULIAR SERVICES
*** AVERAGE COST FOR THIS MISSION MODEL

Table 3-10. SPACE TUG SYNCHRONOUS EQUATORIAL PERFORMANCE CHARACTERISTICS

SPACE TUG DESIGNATION	IMPULSE PROP. WEIGHT (LB)	PAYLOAD DELIVERY AND RETRIEVAL CAPABILITY * (LB)			
		MODE 1	MODE 2	MODE 3	MODE 4
AGENA	13,400	-	-	-	2,550
D-IT CENTAUR	30,000	-	-	-	13,318
G T CENTAUR	45,000	-	-	-	21,208/18,710
LG TANK AGENA	51,100	-	-	-	14,397
LO_2/LH_2	30,000	-	280	790	14,418
LO_2/LH_2	36,300	1016	1403	3,680	17,500
LO_2/LH_2	43,000	1400	1997	5,777	21,320/19,740
LO_2/LH_2	50,200	2475	3418	8,966/8,840	25,250/18,850
LO_2/LH_2	57,700	3237/2827	4471	11,725/7,384	29,472/18,290
LO_2/LH_2 (I_{SP} = 444)	50,200	1640	2320	6,840/5,860	23,600/18,530
LO_2/LH_2 (I_{SP} = 470)	50,200	2645	3680	9,480/9,140	26,640/19,820
$FLOX/CH_4$	44,000	1380	1870	5944	19,430/18,837
$FLOX/CH_4$	52,000	2147	2883	8,411/8,310	22,700/17,640
$FLOX/CH_4$	58,900	2910/2690	3911	11,410/7,825	26,180/17,475
LF_2/LH_2	47,800	3390	4720	12,020/11,890	25,980/20,310
LF_2/LH_2	54,200	4350	6060	15,430/11,314	29,970/20,085
LF_2/LH_2	60,600	5340/4270	7435/7200	18,940/10,840	33,960/19,900

* P/L UNCONSTRAINED TUG IGNITION WT; P/L FOR TUG CONSTRAINED TO 65K LB IGNITION WT

DATA INTEGRATION AND INTERPRETATION

Chapter 4
DATA INTEGRATION AND INTERPRETATION

DATA INTEGRATION

The Space Tug selection problem requires a measurement of the cost, effectiveness, and benefits associated with each candidate Tug or family of Tugs. To do this, a methodology for transforming the characteristics of a candidate system into the performance and total cost of that system is needed. Development of such a methodology was centered around the mission model discussed in Chapter 2.

Relative to this model, Tug effectiveness is defined as a measure of Tug payload capability; it includes measurement of the excess capability over the baseline payload definition, the Tug activity level required to perform the mission model, and the number of Space Shuttle flights to support the Tug operations.

The cost element consists of Tug development, investment, and operations cost; Space Shuttle user fee to support the entire mission model; and development, investment, and operation costs for the entire payload model.

Benefits from the use of the Shuttle/Tug transportation system include those payload cost savings arising from operating within the Shuttle/Tug environment. A detailed definition of each of these elements is presented below, starting with the effectiveness measure since it is the driver for determining the cost and benefits of a candidate Tug.

Tug Performance and Mission Model Accommodation

The accommodation analysis defines the interaction of Tug design, performance, and geometry with payload characteristics such as baseline weights, dimensions, and orbital parameters. This information, together with the Space Shuttle performance definition, produces a program-by-program description of the alternative ways in which individual spacecraft can be deployed and/or retrieved. The output from this analysis serves to define the number of Tug and Shuttle flights required to support the mission model, the Tug fleet size, and the Tug yearly activity levels; all of these are required inputs for the costing of the investment and operations phases.

The four Tug operational modes that were employed for payload deployment and/or retrieval are defined as follows:

<u>Mode 1</u>. Roundtrip delivery of equal weight payloads by one Tug
<u>Mode 2</u>. Retrieval, only, of a payload in one Tug roundtrip flight
<u>Mode 3</u>. Delivery, only, of a payload with (empty) return of the Tug
<u>Mode 4</u>. Delivery of a payload with no Tug return

Evaluation of Tug performance for each of these modes is based upon the equations, presented in Chapter 3, that use as inputs the mission initial and final conditions and the Space Shuttle performance to these initial conditions. (Shuttle performance is an inequality constraint imposed on the Tug ignition weight.) In the application of these equations, a velocity-loss approach is used wherein an approximation of the finite-burn ΔV losses is added to the impulse ΔV schedules specified in the mission model. This approach, currently in use by LMSC in preliminary analysis of the superorbital flight segment of launch vehicles, is based on tabular data relating thrust, weight, and burn time for categorized initial conditions such as low earth orbit with zero flight path angle. These data represent the velocity losses established from previously simulated optimum or constant-attitude superorbital trajectories.

The logic for the evaluation of the Space Shuttle and Space Tug flight requirements to deploy and/or retrieve a defined payload is presented in Table 4-1. The ignition and propellant weight inequalities, combined with the performance equations for the appropriate operational mode, yield the payload capability (P_i). This set of inequalities is based upon the following assumptions:

1. The Space Tug and Shuttle flight requirements are based upon the baseline payload weights.
2. The maximum number of Space Shuttle flights for any payload deployment is three.

Table 4-1 INEQUALITIES USED TO ESTABLISH SHUTTLE AND TUG ACTIVITY LEVELS

Payload Constraint	Ignition and Propellant Weight Constraints	Tug and Payload Length Constraints	No. Tugs/ No. Space Shuttles
$P_1 > BLPL$	$W_{P_1} + W_I + P_1 < W_O \quad W_{P_1} = W_P$	$L_T + L_{PL} < 60$	1/1
$P_2 > BLPL$	$W_{P_1} \quad W_O - W_I - P_2 \quad W_{P_1} \leq W_P$	$L_T + L_{PL} < 60$	1/1
$P_1 > BLPL$	$W_{P_1} + W_I + P_1 < W_O \quad W_{P_1} \quad W_P$	$L_T + L_{PL} > 60$; $L_T < 60$, $L_{PL} < 60$	1/2
$P_3 > BLPL$	$W_{P_1} \quad W_O - W_I \quad W_{P_1} \leq W_P$	$L_T < 60$, $L_{PL} < 60$	1/2
$P_4 > BLPL$	$W_{P_1} + W_{P_2} + W_{I_1} + W_{I_2} + P_4 < W_O$, $W_{P_1} \leq W_P$ $W_{P_2} \leq W_P$	$2\,L_T + L_{PL} < 60$	2/1
$P_5 > BLPL$	$W_{P_1} + W_{P_2} + W_{I_1} + W_{I_2} + P_5 < 2\,W_O$, $W_{P_1} \leq W_O - W_{I_1} \leq W_P$, $W_{P_2} \leq W_O - W_{I_2} \leq W_P \quad P_5 \leq W_O$	$2\,L_T < 60$ & $L_{PL} < 60$ OR $L_T + L_{PL} < 60$	2/2
$P_6 > BLPL$	$W_{P_1} + W_{P_2} + W_{I_1} + W_{I_2} + P_6 < 3\,W_O$ $W_{P_1} \leq W_O - W_{I_1} \leq W_P$ $W_{P_2} \leq W_O - W_{I_2} \leq W_P$ $P_6 \leq W_O$	$L_T < 60$, $L_{PL} < 60$	2/3

DEFINITION OF VARIABLES

- P_i - Payload capability for the candidate Tug
- BLPL - Baseline weight of the specified payload
- W_P - Tug maximum propellant weight
- W_I - Tug wet inert weight
- W_O - Shuttle payload capability to mission initial conditions
- L_T - Total Tug length
- L_{PL} - Length of baseline payload

3. The criterion for Tug configuration selection (single vs tandem configurations and the amount of offloading) is to select the configuration that requires the minimum number of Space Shuttle flights.

In this table the first four sets of inequalities are for single-stage configurations and the remaining three sets are for tandem configurations. For a given payload definition (BLPL and L_{PL}), Tug design (W_P and W_I) and Space Shuttle performance (W_O) these inequalities are searched sequentially (as ordered in this table) until all the inequalities in the set are satisfied. The Space Tug and Shuttle flight requirements corresponding to this set, along with the excess payload capability, are then used as inputs to the payload costing analysis.

Evaluation of the Tug and Shuttle requirements for each payload deployment mode, for each payload in the mission model, completes the accommodation analysis

Total Program Cost

The payload and Tug cost elements were calculated using the following standard cost classifications:

- RDT&E costs
- Investment costs (unit recurring-production)
- Operations costs
- Shuttle user charges

For purposes of economic evaluation, however, the total program costs (and the savings achieved by one Tug relative to another) were reclassified as follows:

Nonrecurring costs

- RDT&E
- Initial investment

Recurring Costs

- Activity-level dependent costs
  - investment
  - operations
- Activity-level-independent operations costs

The manner in which the individual cost elements were allocated between these classifications is summarized in Table 4-2. This classification system makes possible the calculation of mission program savings as a function of total Tug investment and of the effects of activity level.

The rationale for the spreading of Tug and payload costs is discussed in Chapter 3.

Payload Analysis

The Payload Effects Analysis Study, conducted for NASA under Contract NASw-2156, showed that very substantial savings in total program costs could be achieved without loss of mission capability by designing the payload to exploit cost-favorable features of the Shuttle operational environment. In particular, it was demonstrated that a

Table 4-2 CLASSIFICATION OF COST ELEMENTS

NONRECURRING COSTS		RECURRING COSTS		
		ACTIVITY-LEVEL DEPENDENT		ACTIVITY-LEVEL INDEPENDENT OPERATIONS
RDT&E	INVESTMENT	INVESTMENT	OPERATIONS	
ALL CONVENTIONAL DEVELOPMENT COSTS	SYSTEM ACQUISITION • INITIAL REUSABLE FLEET • INITIAL SPARES (BACKUP UNITS) • OPERATIONAL FACILITIES AND EQUIPMENT • SUPPORT COSTS	• EXPENDABLE HARDWARE • REFURBISHMENT HARDWARE • EQUIPMENT MAINTENANCE	• LAUNCH OPERATIONS • LOGISTICS • SUPPORT COSTS FOR PAYLOAD: • TRANSPORTATION COSTS CONSISTING OF TUG AND SHUTTLE USER CHARGES	• GROUND STATION OPERATIONS • SUSTAINING ENGINEERING • MISSION OPERATIONS • FACILITY MAINTENANCE • SUPPORT COSTS
		FOR TUG, TUG USER CHARGE BASED ON THESE COSTS		

majority of the savings achievable by Shuttle type operations was to be found in reduced payload-related costs. Specific major sources of savings were:

- Greatly relaxed weight and volume constraints, enabling use of off-shelf components, simple materials and overdesign (to reduce analysis and testing), modularization, and easily maintainable designs.
- Accessibility – without change in design reliability, the ability to retrieve a payload (or repair it in orbit) if it fails on ascent, permits a reduction in the ground testing conducted to ensure that the reliability has been achieved.
- Retrieval and refurbishment of payloads for reuse, with or without a change in the experiment subsystem.

These effects were demonstrated by redesigning, down approximately to the component level, three representative space payloads which had flown and for which cost data were available. These were:

1. The Orbiting Astronomical Observatory, Model B (OAO-B)
2. The Lunar Orbiter, modified into a Synchronous Earth Orbiter (SEO)
3. The Lockheed Small Research Satellite (SRS)

This approach, performing detailed design studies of three selected representative spacecraft, lent force and credibility to the savings mechanisms identified and their contribution to reduced program costs. It required, however, that further analysis be performed to generalize from these specific spacecraft to the wide spectrum of payloads involved in the Tug Economic Analysis study, and also to allow for certain features peculiar to combined Shuttle/Tug operations.

Weight Effects on Cost. In the design studies described above, weights and volumes of the low cost payloads were essentially unconstrained. This policy was adopted deliberately with the reasonable intent of deriving a fairly well defined point on the curve (or among the possible combinations) of cost versus weight as an anchor point at the opposite end of the range from the conventional baseline design, and specifically, to define a reasonable extreme.

In the context of this study the constraints on the weight and volume of the payload are not fully relaxed because of the high energy nature of Tug missions, because of the weight and volume which must be reserved in the Shuttle bay for the Tug, and also because of the high Tug performance requirements involved in retrieving a payload for refurbishment. Analyses were therefore performed on the data developed during the Payload Effects Study to:

- Fill in the cost-weight relationships between the extremes of baseline and low cost.
- Identify the cost penalty of modularization for refurbishability and separate these from the penalties resulting from low cost design as such.
- Generate cost estimating relationships for baseline and for low-cost payloads.

These analyses were essential to provide a basis for a choice between payload deployment and replacement options such as (1) using light but expensive refurbishable payloads, one of which can be replaced and one returned by a single Shuttle/Tug flight; (2) using heavy, cheap, expendable payloads, and replacing them, when necessary, with new ones.

Cost Estimating Relationships (CERs) were required for the conventional baseline payloads and for the low-cost payloads. The CERs for the baseline payloads were first assembled by subsystem for the following classifications of cost elements:

- Nonrecurring costs
- Unit cost
- Activity-level-dependent operating cost, per launch
- Activity-level-independent operating cost, per year

Figure 4-1 illustrates a typical baseline payload CER derived from the historical data base and corrected to 1970 dollars. As is conventional, these data were referenced to subsystem weights. These required weights for the subsystems of each payload were obtained, where possible, from analyses performed for NASA by the Aerospace Corporation. Data not available from this source were generated by LMSC as part of the present study.

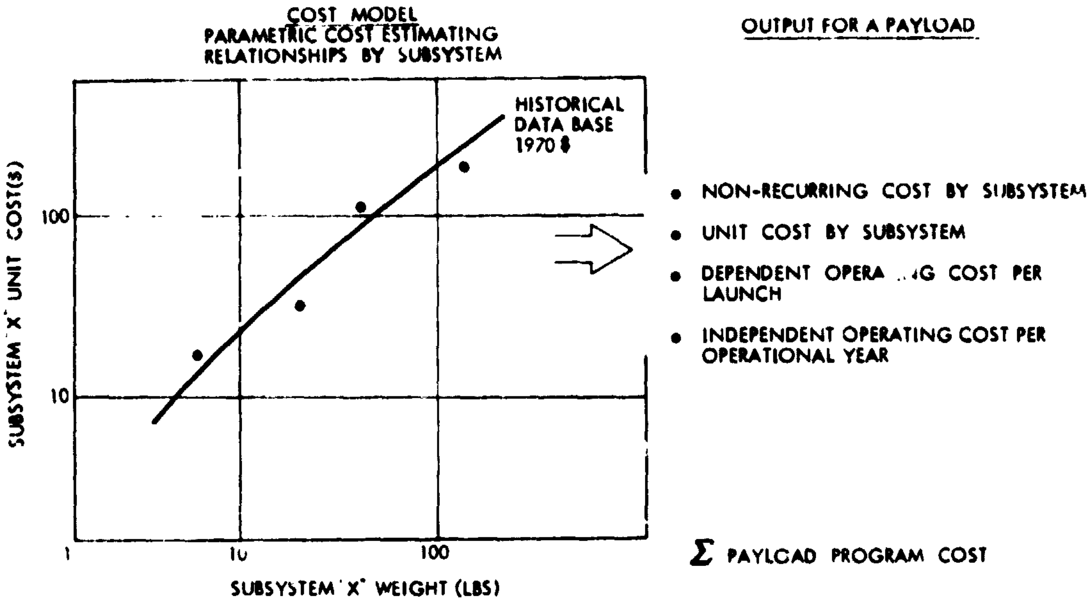


Figure 4-1 Baseline Payload CER

CERs for the low cost payloads were generated in two steps:

1. Algorithms were developed relating the weight of a low cost subsystem to the weight of the corresponding conventional subsystem.
2. New cost-versus-weight curves were generated, using the data points from the Payload Effects Study correlated with the data for conventional subsystems.

The curves generated under (2) covered low-cost payloads either for Shuttle launch or for launch from a Low-Cost-Expendable booster. An example is presented in Figure 4-2. The conventional subsystem has a cost C and a weight K. After removal of weight and volume constraints by use of the Low-Cost-Expendable booster, but without exploiting all the benefits inherent in the Shuttle operating environment, the cost can be reduced

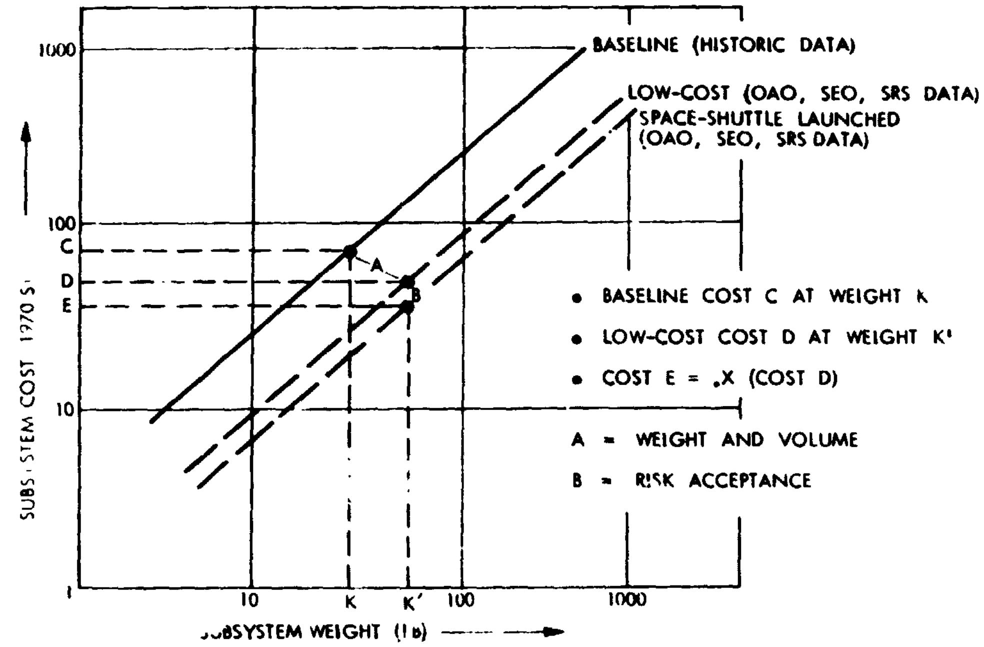


Figure 4-2 Sample Low-Cost Weight and Cost Estimating Relationships

to D at constant capability provided that the weight is allowed to increase* to K'. With Shuttle launch, cost can be further reduced to E, at no increase in weight by the accessibility strategy, discussed in the next section. Thus, a family of curves such as those sketched in Figure 4-2, gives subsystems cost data for baseline payloads, for low-cost payloads designed essentially without weight and volume restraints, and for low-cost payloads with accessibility savings. It should be noted that as a result of the ground rules under which the Payload Effects Analysis Study was conducted, the weight penalties defined by the algorithms for the full-low-cost designs include a portion of the weight required for refurbishability. This also is further discussed below.

*It is important to recognize that this increase in weight is necessary to maintain capability while changing to low-cost design (along line A). Thus, computation of this weight increase from K to K' is an essential part of the procedure.

Accessibility. When a payload that fails to work immediately after being emplaced and activated can be corrected on the spot or retrieved and returned to earth by the same Shuttle flight for repair, it is economically profitable to omit some of the test procedures whose purpose is to confirm that the vehicle has achieved its design reliability. It is emphasized that this cost saving involves no design change to reduce reliability, only a reduction in testing designed to demonstrate reliability. This is the cost reduction represented by D – E in Figure 4-2.

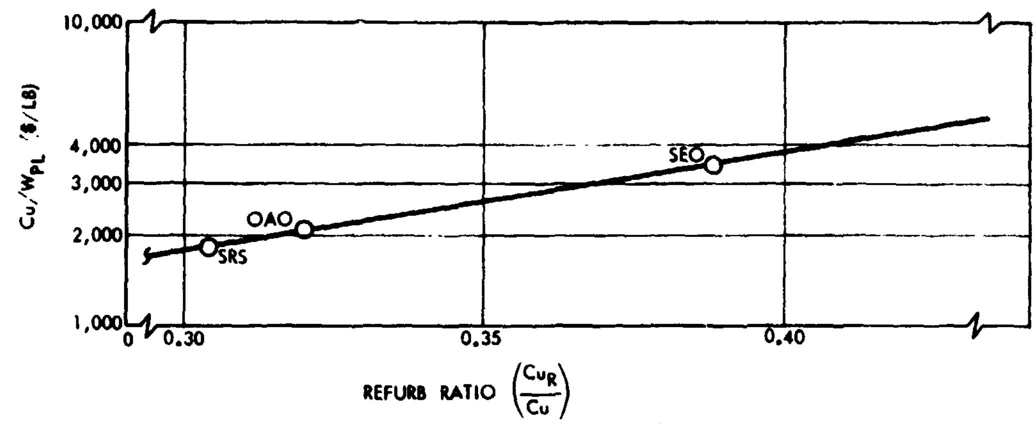
In Shuttle/Tug operations, however, two cases can arise.

1. If the Tug, having placed the payload, can bring it back to the Shuttle should it fail to function, the full accessibility cost saving can be achieved.
2. If the payload can be retrieved solely from the Shuttle orbit because the Tug is incapable of returning it from its final orbit, only part of the accessibility cost saving can be achieved.

Analyses of the time distribution of failures during launch, during ascent, and on orbit show that in case (2) it is representative to assume that 40 percent of the potential accessibility savings can be achieved.

Refurbishability. For a payload to be economically refurbishable, whether on orbit or after return to earth it must be designed in a modular manner and in such a way that its modules are accessible. This entails a weight penalty. This penalty was estimated for the three payloads (OAO, SEO, SRS) by the staff who conducted the Payload Effects Study and these estimates were generalized into refurbishment weight penalty algorithms in the present study. Studies of the dollar cost of refurbishment were similarly generalized (Figure 4-3). Using these relationships, estimates could be made of the cost and weight of payloads as follows:

- Baseline – nonrefurbishable
- Baseline – refurbishable
- Low cost – nonrefurbishable
- Low cost – refurbishable



$$Cu_R = \frac{Cu}{3.12}\left(\log_{10}\frac{Cu}{W_{PL}} - 2.30\right)$$

Cu is LOW COST UNIT COST

Cu_R is REFURBISHED UNIT COST

W_{PL} is WEIGHT OF PAYLOAD

Figure 4-3 Algorithms for Refurbishment

The next step was to estimate cost versus weight for payloads falling between the baseline and the full-low-cost cases.

Cost Versus Weight Interpolation. Because the capability of any Tug/Shuttle combination is limited, especially in an operating mode where one payload is placed and another returned on the same flight, it is inevitable that the Tug/Shuttle weight capability will fall between that for round trip operation of a baseline payload and that for round trip operation of a full low cost payload. In such a case it could be misleading to assume that no weight/cost options are available between these extremes.

The relationship between payload cost and weight is in effect a potential weight investment program in which available excess weight capability is applied at those points in the payload that give the best payoff in reduced cost. There are decreasing returns in cost reduction as weight is increased since the most profitable investments would be exploited first. In the early phase of the Payload Effects Study a hyperbolic relationship was assumed as shown in Figure 4-4, which involved two abstractions, an asymptotic minimum weight regardless of cost and an asymptotic minimum cost regardless of weight. (It is important to realize that these are abstractions without any precise real-life equivalent.)

The Payload Effects Study only went to the subsystem level, that is, each subsystem was either baseline or low cost. Insufficient resources were available to proceed to greater detail (e.g., to a partially-low-cost guidance system) but some evidence was required from which to derive a system-level cost/weight relationship. The approach adopted was to assume that individual subsystems could be made low cost provided that additional weight in the structures, attitude and control, and (if relevant) propulsion subsystems was added pro rata. The total structure subsystem weight increase was divided into a part to be prorated against other subsystems and a part to provide a low cost structure. Sufficient weight was assumed to be added to the attitude control system to maintain its cost at a constant level, which is essentially what happened in the low cost cases.

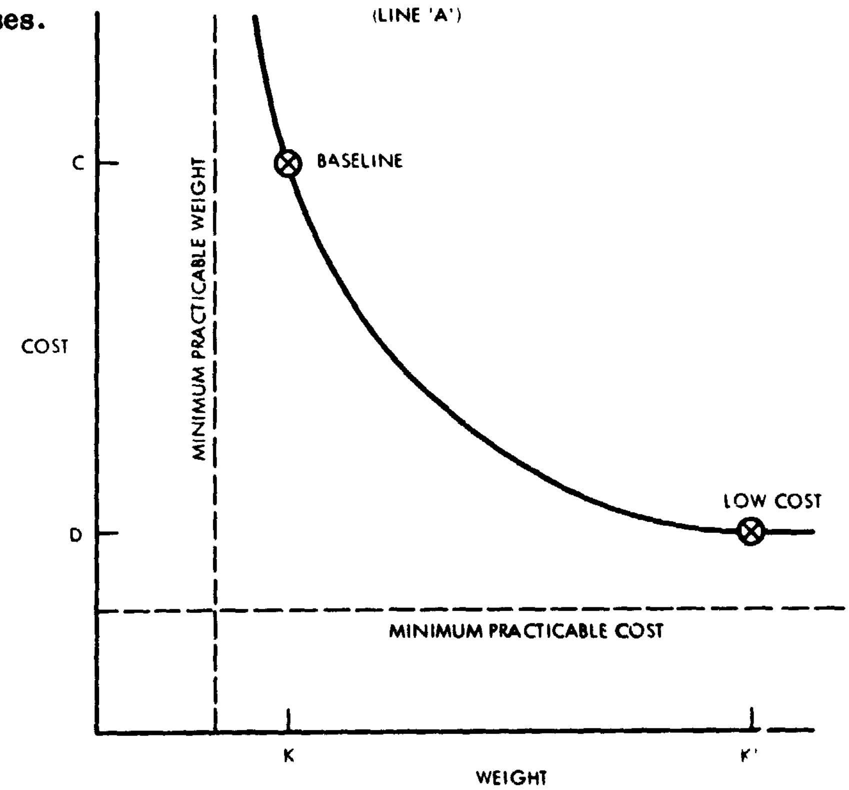


Figure 4-4 Theoretical Basis of Low-Cost Design

It was found that for the SEO and SRS the cost/weight relationship was represented by the expression:

$$\left(\$ - \frac{\$ \text{ low cost}}{1.2}\right)^{1/3} + \left(W - \frac{W_{basic}}{1.2}\right)^{2/3} = \text{constant}$$

for both unit and RDT&E cost. In the case of the OAO the savings in the stabilization and control subsystem was so large and dominant as to make this payload unrepresentative. This discrepancy resulted from the extremely stringent requirements imposed on the original stabilization and control system. For application to the Tug Economics study, however, it was not convenient to have an infinite range of possible weights for each payload. A modified approach permitting selection among five cost-weight combinations, was adopted. This approach is illustrated in Figures 4-5 and 4-6 for unit cost and RDT&E cost, respectively. The data shown for the three payloads from the Payload Effects Study were derived in the same manner as described above. Again, the OAO differed drastically from the others because of the extreme dominance of the costs of the stabilization and control subsystem in that mission. The cost versus weight relationships for the SEO and SRS, however, are quite representative of the bulk of the Tug missions and agree rather well. The relationships represented by the heavy lines in Figures 4-5 and 4-6 were selected as adequately representative for the present parametric analyses and were programmed into the ANNEX data integration program.

Volume Requirements. The payload dimensions used in the mission model resulted from configuration of the payloads to meet the constraints imposed by existing, conventional launch systems. This resulted in a marked tendency to emphasize constraints on diameter rather than on length. In the Shuttle/Tug environment, however, the emphasis tends to be reversed; the available diameter becomes more generous, and the available length is constrained by Tug propellant volume requirements. As illustrated in Figure 4-7, 17 percent of the mission model payloads were potentially too long to fit in the Shuttle bay with a Tug, even without any volume increases required

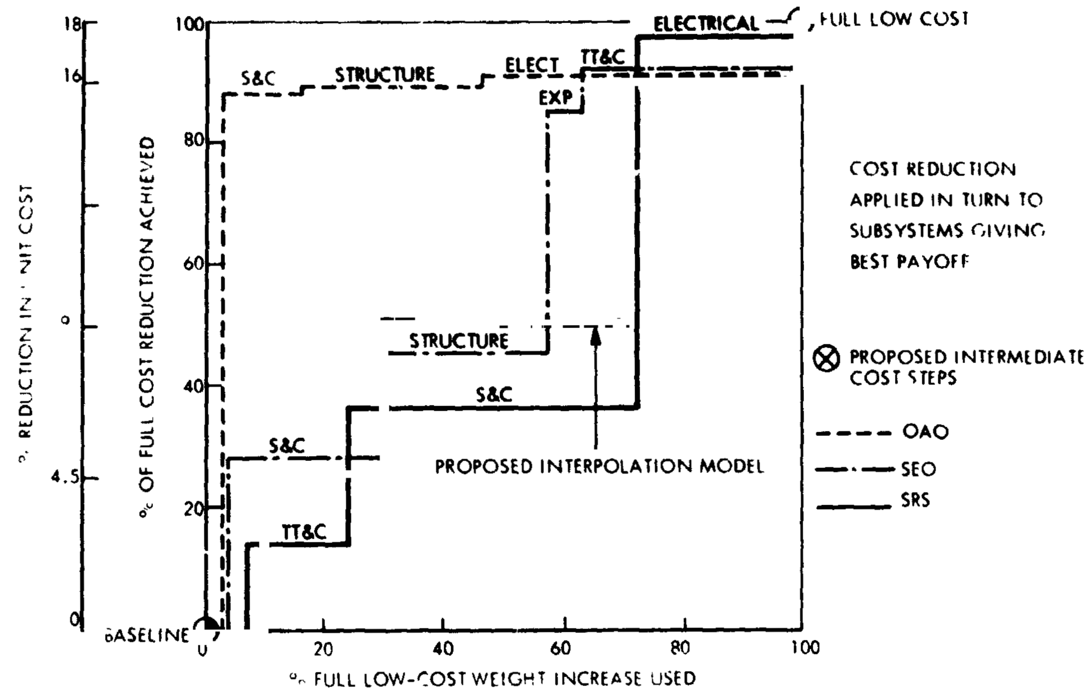


Figure 4-5 Unit Cost vs Weight Interpolation

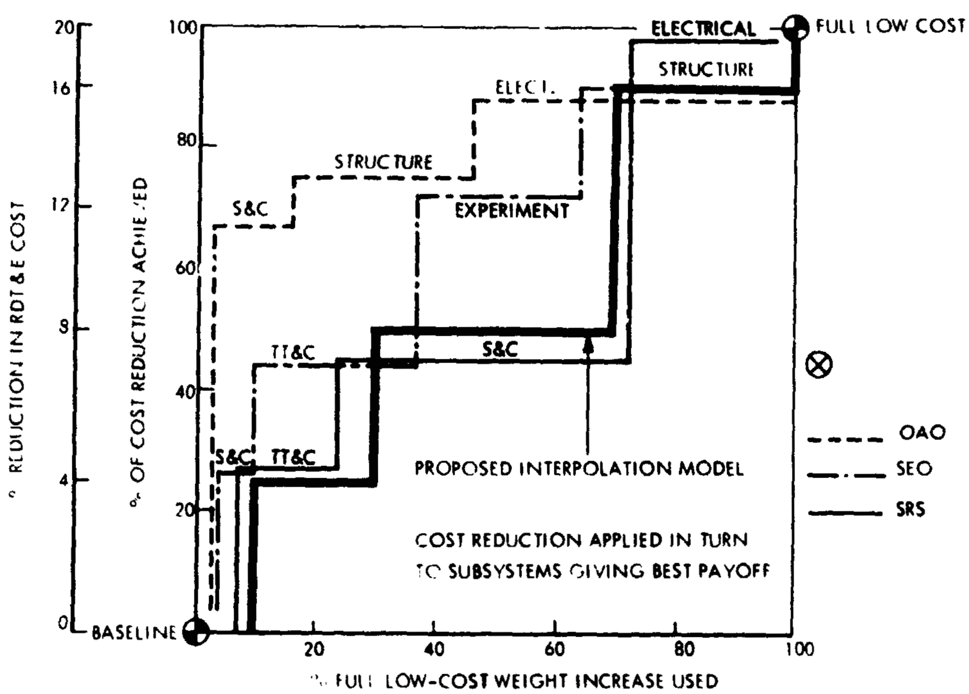


Figure 4-6 RDT&E Cost vs Weight Interpolation

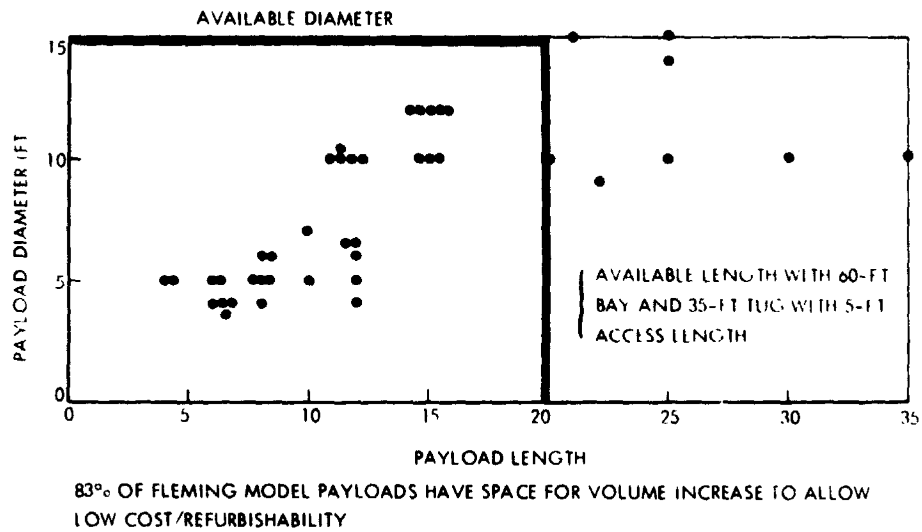


Figure 4-7 Payload Dimensions vs Available Cargo Bay Dimensions

by refurbishability or by low cost design. A simple methodology was therefore developed to reconfigure the baseline payloads to fit into the Shuttle in either the baseline, refurbishable, or low-cost forms.

This methodology is illustrated in Figure 4-8. The payload was assumed to consist of:

1. A possible experiment section whose diameter and/or length was dictated by the mission and was unaffected by application of low-cost techniques (such as a telescope whose aperture and length were fixed).
2. An equipment section which could be of any shape but whose density was unaffected by changes in shape.

After review of the design work performed under the Payload Effects study it was decided that:

- Design for refurbishability would increase the volume of the equipment section by 50 percent.

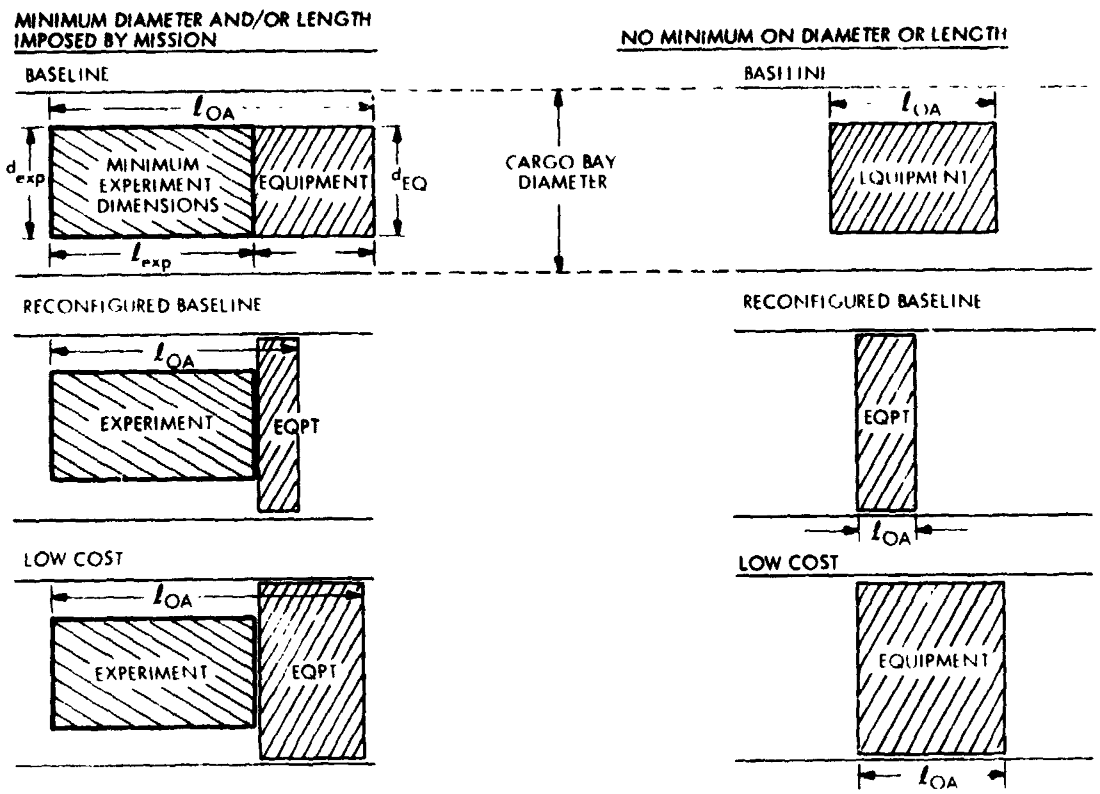


Figure 4-8 Dimensional Reconfiguration of Large Payloads

- Design for low cost would increase the volume of the equipment section by 100 percent, whether it was refurbishable or not.
- Partial low cost, as in Figure 4-5, would increase volume linearly with the weight, between the baseline case and the full-low-cost case.

The rules were mechanized in the ANNEX subroutine to the STAR (discussed subsequently). Adjustments were made manually based on inspection of critical cases.

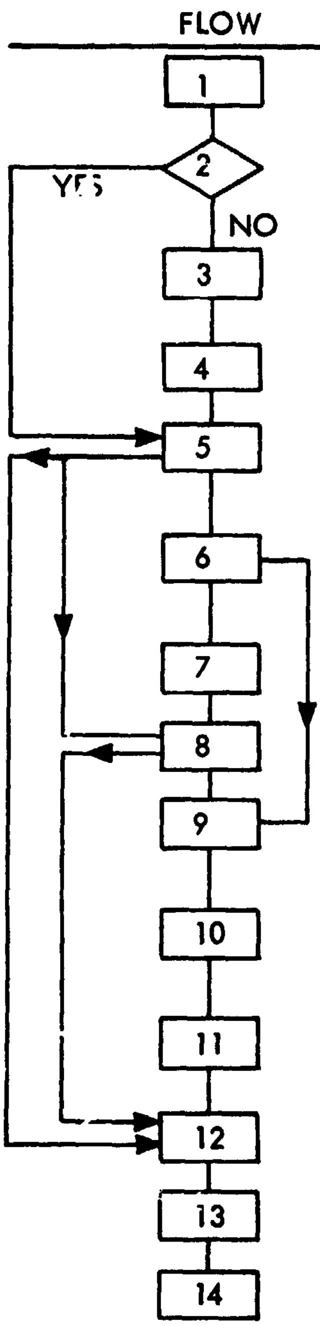
Computer Software

The process by which Lockheed processed and interpreted information from the data base involved a close man/machine interaction. High-speed computer programs were used extensively so the widest possible numbers of variables could be incorporated into the analysis while maintaining a short turnaround time for individual cases. Lockheed used as its primary computer program the Space Transportation Analysis Routine (STAR) and a subroutine designated ANNEX that calculates total program costs. STAR and ANNEX are not optimization programs, but rather computational tools designed to extend the efficiency of systems engineers. Individual runs of STAR/ANNEX were made for each Tug configuration or sensitivity variation being studied. At the conclusion of each sequence of runs the data evaluation team reviewed printouts to determine cost-driving factors such as the number of Shuttle flights, Tug flight-mode shifts, and Tug inventory requirements.

An overall flow diagram for the STAR/ANNEX program is presented in Figure 4-9. There are five major sections in this program, each drawing upon information stored in the data bank or generated by the previous analysis. The process is initiated by calling upon appropriate stored or input data that serves to configure a candidate Tug design. The options available for the configuration of a Tug are:

1. Specification of Tug propellant weight, in which case the design routine is exercised to generate a point design for that propellant weight. (Steps 2 and 5 in Figure 4-9.)
2. Stage sizing through specification of the ignition weight of the Tug and its operational mode. In this case the design routine is exercised to generate an inert-weight/mass fraction relationship that is used in the performance equations, listed previously, to generate Tug propellant weights. The Tug point design is then synthesized using this propellant weight with the design estimating relationships (Steps 3, 4, and 5 in Figure 4-9).

Through the accommodation analysis (step 6) the performance characteristics of the point design Tug are assessed in relationship to the Space Shuttle definition and the mission model. In addition to the performance assessment, the Tug and Shuttle flight requirements are identified, and the compatibility between Tug, spacecraft, and Shuttle are evaluated for the four basic flight operational modes for each of the programs in the mission model. This output allows an initial vehicle-activity estimate that in turn sets up the information for a preliminary Tug costing and determination of an initial user Tug user fee (steps 7 and 8). The following section (step 10) evaluates payload effects captured, their associated costs, and a program-by-program definition of the most cost-effective flight operational mode (step 11). Output of this section updates the vehicle activity requirements, this in turn redefines the Tug cost estimates (step 12).



STEP	SOURCE
1. CASE INPUTS	INPUT
2. TEST FOR FIXED STAGE PROPELLANT WEIGHT	
3. GENERATION OF STAGE MASS FRACTION RELATIONSHIP	DESIGN ROUTINE
4. STAGE SIZING	PERFORMANCE ROUTINE
5. POINT DESIGN EVALUATION	DESIGN ROUTINE
6. SPACE TUG ACCOMMODATION & CAPABILITY ANALYSIS	MISSION MODEL & MISSION CAPTURE ROUTINE
7. PRELIMINARY SPACE TUG FLEET SIZE EVALUATION	MISSION CAPTURE ROUTINE
8. TUG COST EVALUATION	COST ROUTINE
9. PAYLOAD COSTING BY MISSION & MODE	ANNEX SUBROUTINE
10. TOTAL PROGRAM COST BY MODE & BEST MODE MIX	ANNEX SUBROUTINE
11. NEW FLEET SIZE REQUIREMENTS	MISSION CAPTURE ROUTINE
12. REVISED TUG OPERATIONS COST	COST ROUTINE
13. TUG COST SUMMARY	COST ROUTINE
14. TOTAL PROGRAM COST SUMMARY	MISSION CAPTURE ROUTINE

Figure 4-9 STAR Logic

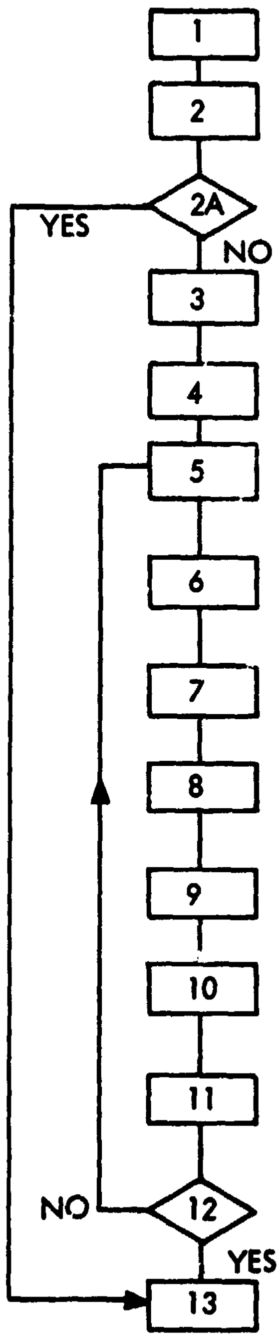
The last section serves to summarize the Tug and total-program costs, and supplies the pertinent information required for the economic analysis.

Each of the four major components of this STAR/ANNEX program, beginning with the Tug Design Routine, is discussed in the following paragraphs.

Tug Design Routine. A flow diagram of the steps comprising the Tug design routine is presented in Figure 4-10. Initiation of this routine requires the input of the Tug type and propellant weight, Tug lifetime, and basing mode. With this information the appropriate data required to synthesize the Tug is retrieved from the data bank. If the specified Tug is an orbit injection stage, the retrieved design data represents the stored point design of that Tug and the routine proceeds to output the Tug characteristics (step 13). If a reusable Space Tug is to be synthesized then steps 3 through 12 are exercised. In these steps the design estimating relationships are used to configure the weight and geometric characteristics of the Tug. The required iteration in these steps is the result of the load-carrying components of the Tug being sized prior to knowing the total weight of the stage. For the Tugs synthesized in this study two to three iterations were sufficient for convergence. A representative point design weight statement from this routine is presented in Table 4-3 for a ground based reusable LO_2/LH_2 Tug sized for a 50,200 lb propellant weight. For this configured stage, the geometric characteristics are presented in Figure 4-11 relative to the 15 ft by 60 ft payload bay of the Space Shuttle.

Tug Accommodation Routine. An overview of the sequence of steps accomplished in the Tug performance and accommodation routine is presented in Figure 4-12. Retrieval of the mission and payload data (step 1) initiates the evaluation of the Tug performance relative to a given mission and payload. The compatibility tests between the payload Tug and Space Shuttle screen out those payload and Tug characteristics that would prevent the use of the Space Shuttle (step 2). In steps 4 through 8 the Tug performance to the mission conditions and the Shuttle and Tug flight requirements are evaluated for each applicable payload deployment and/or retrieval mode. This information is stored in a common block and the relative data is output. A representative performance accommodation output for the 50,200 lb propellant LO_2/LH_2 Tug is presented in Table 4-4

FLOW



STEP	SOURCE
1. SET DESIGN OPTIONS	INPUT
2. RETRIEVE TUG RELATED DESIGN DATA	DATA BANK
2A. TEST TO SEE WHETHER VEHICLE IS AN ORBIT INJECTION STAGE	
3. EVALUATE TUG GEOMETRY BASED ON INPUT PROPELLANT LOAD	STAR
4. INITIAL APPROXIMATION OF STAGE WEIGHT (TWG)	
5. EVALUATE TANK WEIGHTS	
6. EVALUATE ENVIRONMENTAL PROTECTION SYSTEM BASED ON INPUT TUG LIFETIME, GEOMETRY, & TANK GEOMETRY	INPUT
7. EVALUATE STRUCTURE WEIGHTS	
8. EVALUATE PROPULSION CHARACTERISTICS BASED ON SPECIFIED PROPULSION PARAMETERS	INPUT
9. EVALUATE AVIONICS & ELECTRICAL POWER REQUIREMENTS	
10. EVALUATE CONSUMABLES & NON-CONSUMABLES	
11. SUM FOR TOTAL STAGE GROSS WEIGHT (TW), INCLUDING WEIGHT CONTINGENCY	
12. $\lvert TWG - TW \rvert < \epsilon$ (CONVERGENCE VALUE)	
13. OUTPUT STAGE GEOMETRY & WEIGHT STATEMENT	

Figure 4-10 Design Routine Logic

Table 4-3 WEIGHT STATEMENT FOR LO_2/LH_2 REUSABLE GROUND-BASED TUG (50,200 lb Propellant)

STRUCTURE			2432.3	
FUEL TANK		564.7		
OXIDIZER TANK		246.2		
SLOSH BAFFLES		48.8		4
TRUSS STRUCTURE FRAME		483.8		
ENGINE THRUST STRUCTURE		213.1		
OXIDIZER TANK SUPPORTS		84.7		4,5
FUEL TANK SUPPORTS		23.1		4,5
DOCKING CONE		214.8		2
P/L DOCKING MECHANISM		155.5		2
METEOROID PANELS		.0		3
AVIONICS SUPPORT RING		390.8		
INTERSTAGE STRUCTURE		.0		
THERMAL PROTECTION			639.0	
FUEL TANK INSULATION WT		47[illegible].7		4,7
OXIDIZER TANK INSUL. WT		97.3		4,7
THERMAL CONTROL COATING		63.0		4
PROPULSION			963.4	
MAIN ENGINE		357.0		10,11
THRUST VECTOR CONTROL		45.0		9
PROPELLANT ORIENTATION		33.8		4
PROPELLANT MANAGEMENT		46.6		4
PRESSURIZATION (INCL HE)		67.3		4,8
FILL AND DRAIN,FEED,VENT		54.8		9
ZERO-G VENT SYSTEM		36.6		4,6
REACTION CONTROL SYSTEM		263.5		
PNEUMATICS		3[illegible].6		
AVIONICS			748.0	
DATA MANAGEMENT		43.0		
COMPUTER (32K)	32.0			
INPUT/OUTPUT	6.0			
SWITCHING LOGIC	5.0			
NAVIGATION AND CONTROL		36[illegible].0		
INERTIAL SENSOR ASSY	76.0			
HORIZON SENSOR	44.0			
STAR TRACKER	66.0			
FLIGHT ELECTRONICS	30.0			
RF INTERFACE	20.0			
RENDEZVOUS RADAR	110.0			
DOCKING RADAR	40.0			
COMMUNICATION		112.0		
RECV,DECOD,TRANSM,MISC	82.0			
RECORDER	30.0			
INSTRUMENTATION		2[illegible].0		
WIRE AND CONTINGENCIES		187.0		
ELECTRICAL POWER			274.8	3
BATTERIES		.0		
FUEL CELLS		143.6		
RADIATOR		92.5		

Table 4-3 (Continued)

FUEL CELL REAC. TANKAGE	[illegible].7		
CONTINGENCY (10%)		937.7	
DRY WEIGHT	5985.1		
NON-USABLE FLUIDS		699.3	1.4
FUEL GAS RESIDUALS	16[illegible]		
OXIDIZER GAS RESIDUALS	2[illegible]5.0		
OUTAGE	25[illegible].6		
TRAPPED LIQUID	63.[illegible]		
BURNOUT WEIGHT		6684.4	
CONSUMABLES		51140.8	
USABLE PROPELLANT	51[illegible].0		
ENGINE CHILLDOWN S/S LOS	4[illegible].0		1
VENTED PROPELLANT	34.[illegible]		1
RCS PROPELLANT	4[illegible]		1.9
FUEL CELL PROPELLANT	64.1		1
PNEUMATIC HELIUM	[illegible].5		
GROSS STAGE WEIGHT		57825.2	
STAGE MASS FRACTION		.8734	

REFERENCES

1) AEROSPACE CORP., CHEMICAL ORBIT-TO-ORBIT SHUTTLE MASS PROPERTIES TOR-0059, (6759-01)-4, 14 AUG 70
2) 6TH AEROSPACE MECHANISMS SYMPOSIUM J. C. JONES: NEUTER DOCKING MECHANISM STUDY, 9-10 SEPT 71
3) BOEING CO., CR-[illegible] VOL 1. 26 FEE 71
4) LMSC, ADVANCED MANEUVERING PROPULSION SYSTEM, LMSC A960593, VOL II, 1118, JAN 70
5) LMSC, CRYOGENIC TANK SUPPORT EVALUATION, NASA CR-72533, 15 APRIL 69
6) LMSC, LIQUID PROPELLANT THERMAL CONDITIONING SYSTEM, LMSC-A[illegible], 20 APRIL 67
7) LMSC, PROPELLANT SELECTION FOR UNMANNED S/C PROPULSION SYSTEMS, NASA CR-135203, 15 SEPT 69
8) MACDAC, PRESSURE SENSING CONTROL DEVELOPMENT FOR PRESSURIZATION AND VENTING SYSTEMS, NASA CR-72748, MARCH 71
9) NAR PRE-PHASE A STUDY FOR AN ANALYSIS OF A REUSABLE SPACE TUG, VOL 4, SD71-292-4, 22 MARCH 71
10) PRATT-WHITNEY, O2/H2 AND F2/H2 ROCKET ENGINE PARAMETRIC DATA, PDS-2687, JAN 68
11) PRATT-WHITNEY, PARAMETRIC PERFORMANCE STUDY FOR ROCKET ENGINES USING SPACE STORABLE PROPELLANTS, AUG 1967

Table 4-3 (Continued)

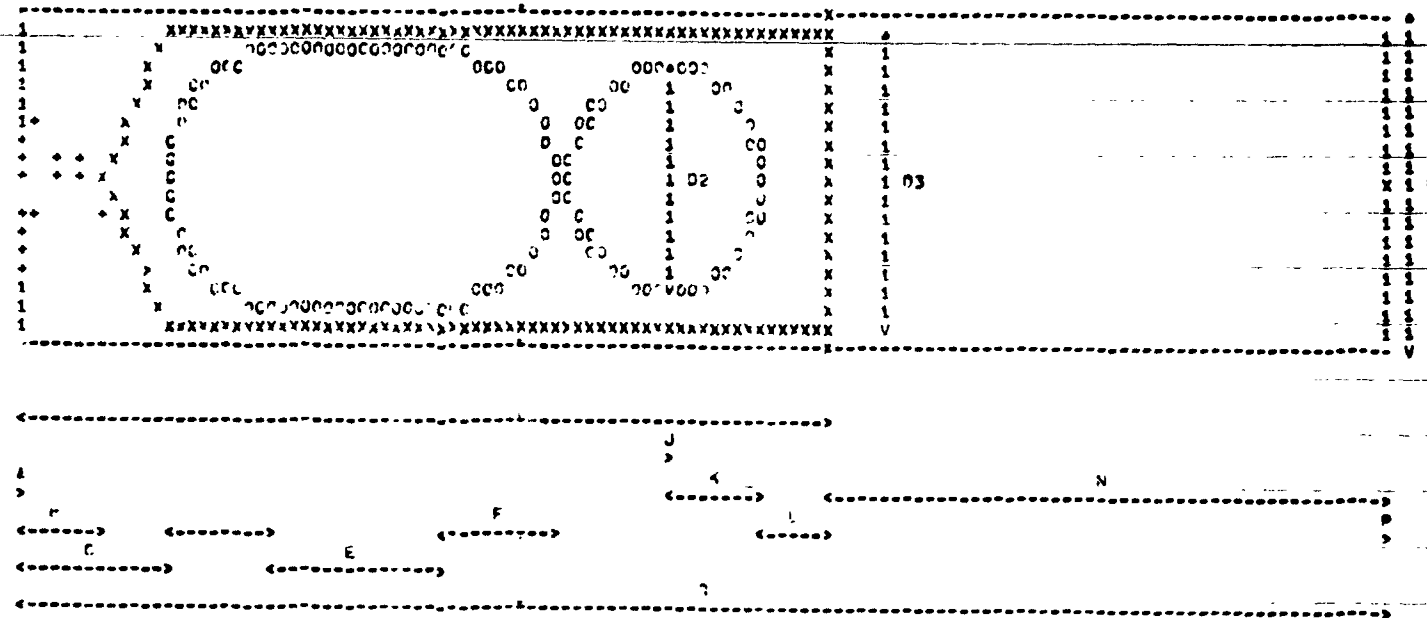
ENGINE CHARACTERISTICS

	PROPELLANT TYPE	MIXTURE RATIO (O/F)	OX DENSITY	FUEL DENSITY
MAIN ENGINE	LO2/LH2	5.5/1	70.80 LBS/FT3	4.38 LBS/FT3
REACTION CONTROL SYSTEM	N204/MMH			

```
MAIN SYSTEM
   DESIGNATION               RETRACTABLE BELL
   SOURCE                    REFS. 9, 10
OPERATING CONDITIONS/ENGINE
   VACUUM THRUST                  20000. LBS
   VACUUM SPECIFIC IMPULSE          460. SEC
   FLOW RATE                      43.48 LB/SEC
   EXPANSION RATIO                200/1

REACTION CONTROL SYSTEM
   DESIGNATION                  SEPARATE
   SOURCE                        REF. 9
OPERATING CONDITIONS/RCS
   VACUUM THRUST
   VACUUM SPECIFIC IMPULSE         274. SEC
   FLOW RATE
 VOLUME      OXIDIZER TANK =    621.17  FUEL TANK =    1957.81
 HEIGHT      OXIDIZER TANK =      9.39  FUEL TANK =      16.86
 DIAMETER    OXIDIZER TANK =     11.67  FUEL TANK =      13.50
 TANK AREA   OXIDIZER TANK =    3[illegible].[illegible]1  FUEL TANK =     772.15
 STAGE DIAMETER =        15.00
 AREA OF CYLINDER + CONES =   1328.51
 STAGE TOTAL LENGTH =      35.45
```

LO2/LH2 WP=50158



BULK HEAD ELLIPSE RATIO IS 1.4142

PAYLOAD LENGTH (FT)	TANK TYPE	TANK LENGTH (FT)	HEAD VOL. (FT3)	CYL. VOL. (FT3)	TOTAL VOL. (FT3)	ULLAGE VOL. (FT3)	NET TANK LIQUID (FT3)	STORED LIQUID (LB)	RESIDUAL LIQUID (LB)	TOTAL IMPULSE (LB)	SPECIFIC IMPULSE (SEC)
.00	FUEL	14.4	913.9	1047.6	1958.5	97.9	1859.9	8146.4	45.7	8100.7	460.0
.00	OX	8.4	618.8	.0	618.8	12.4	606.7	43299.5	6.2	43093.2	

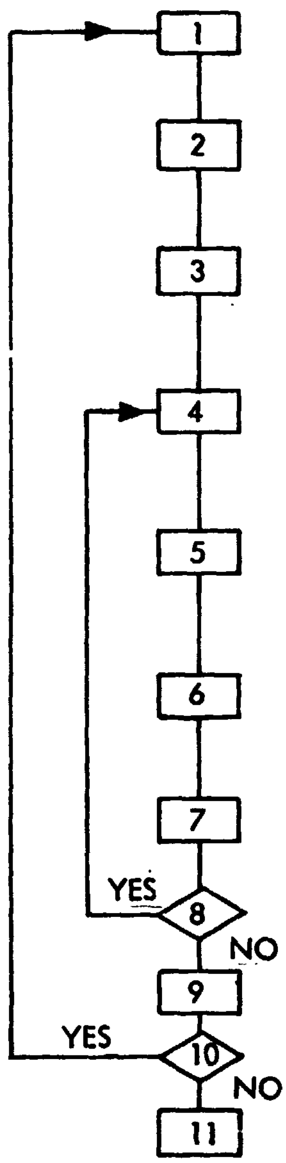
GEOMETRY OF TANKS

DIMENSION	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	Q
IN FEET	.0	3.6	6.4	4.8	7.3	4.8	8.4	.8	4.2	.0	4.2	3.0	35.4	.0	.0	60.0
IN INCHS	.0	43.0	77.3	57.3	87.6	57.3	100.7	9.0	50.3	.0	50.3	36.0	425.4	.0	.0	720.0

DIMENSION	D1	D2	D3	D4
IN FEET	13.5	11.9	14.0	15.0
IN INCHS	152.0	142.4	168.0	180.0

SINGLE STAGE LO2/LH2

Figure 4-11 Typical LO_2/LH_2 Tug Sizing Output



FLOW	STEP	SOURCE
	1. RETRIEVE FIRST/NEXT MISSION & PAYLOAD DATA	MISSION MODEL
	2. COMPATIBILITY TEST BETWEEN MISSION, P/L, TUG, AND SPACE SHUTTLE	INPUT DATA
	3. EVALUATE SPACE SHUTTLE PERFORMANCE TO MISSION INITIAL CONDITIONS	
	4. EVALUATE SINGLE & TANDEM STAGE UNCONSTRAINED AND CONSTRAINED PERFORMANCE FOR FIRST/NEXT MODE	PERFORMANCE EQUATIONS
	5. DETERMINE THE NUMBER OF SPACE SHUTTLE DELIVERY FLIGHTS BASED ON PERFORMANCE RESULTS (NSP)	
	6. DETERMINE THE NUMBER OF SPACE SHUTTLE DELIVERY FLIGHTS BASED ON TUG, PAYLOAD AND SHUTTLE GEOMETRY (NSG)	
	7. NUMBER SPACE SHUTTLE FLIGHTS = MAX (NSP, NSG)	
	8. IS THERE ANOTHER MODE FOR THIS MISSION?	
	9. PRINT MISSION CAPTURE DATA	
	10. IS THERE ANOTHER MISSION?	
	11. PRINT SUMMARY OF TUG MISSION-CAPTURE BY MODE	

Figure 4-12 Performance and Accommodation Routine Logic

Table 4-4 TYPICAL OUTPUT OF PERFORMANCE/ACCOMMODATION ANALYSIS (50,200 lb LO_2/LH_2 Reusable Tug)

MISSION FLEMING NUMBER = 2

	INITIAL CONDITIONS	FINAL CONDITIONS
HE/HA	100./100.	19323./19323.
INCL.	28.5	28.5

DELTA VELOCITY (IDEAL/ACTUAL) = 12950./13156.FPS
APPLICABLE MODE(S) 1 2 3 4

TUG MISSION DURATION
EXPENDABLE 5.25 REUSABLE 12.50 TO 18.50 MAXIMUM 48.00

P/L CHARACTERISTICS	BASELINE NOMINAL	MODE 1 MAX.	MODE 1 Δ IN %	MODE 2 MAX.	MODE 2 Δ IN %	MODE 3 MAX.	MODE 3 Δ IN %	MODE 4 MAX.	MODE 4 Δ IN %
WEIGHT(EXP/REL)	[illegible]./ 1474.	3967.	169.07	5511.	280.60	11868.	1233.54	21321.	2295.57
DIAMETER	5.0	15.00	200.02	15.00	200.02	15.00	200.02	15.00	200.02
LENGTH	4.0.	24.55	513.93	24.55	513.83	24.55	513.83	24.55	513.83
DENSITY	11.3.	.21	-91.91	.21	-88.56	.21	-75.40	.21	-56.52
SS/TUG REQUIREMENTS									
TUG PROPELLANT WT		50158.		50158.		47003.		38293.	
TUG IGN. WT.		60409.		56442.		65000.		65000.	
NUMBER OF TUGS		1		1		1		1	
NUMBER OF SS FL		1		1		1		1	

MISSION FLEMING NUMBER = 3

	INITIAL CONDITIONS	FINAL CONDITIONS
HE/HA	100./100.	180./ 1800.
INCL.	90.0	90.0

DELTA VELOCITY (IDEAL/ACTUAL) = 2500./ 2525.FPS
APPLICABLE MODE(S) 1 2 3 4

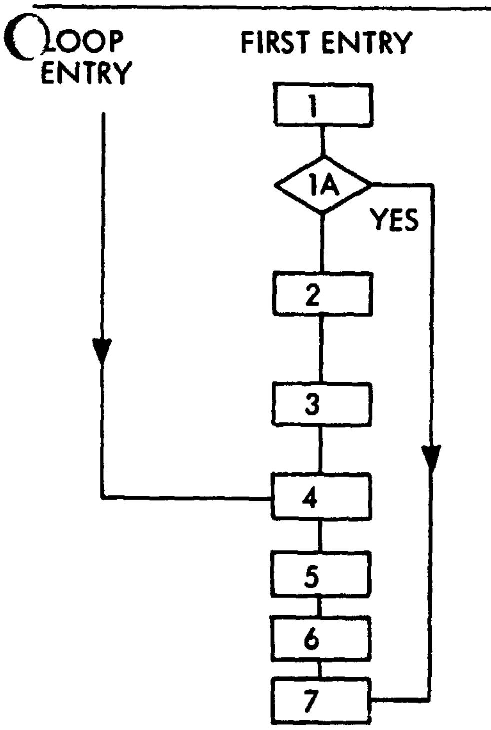
TUG MISSION DURATION
EXPENDABLE .74 REUSABLE 3.48 TO 9.48 MAXIMUM 48.00

P/L CHARACTERISTICS	BASELINE NOMINAL	MODE 1 MAX.	MODE 1 Δ IN %	MODE 2 MAX.	MODE 2 Δ IN %	MODE 3 MAX.	MODE 3 Δ IN %	MODE 4 MAX.	MODE 4 Δ IN %
WEIGHT(EXP/REL)	1200./ 2129.	13321.	525.69	27584.	1195.57	15986.	1232.17	17869.	1389.07
DIAMETER	4.[illegible]	15.00	275.02	15.00	275.02	15.00	275.02	15.00	275.02
LENGTH	[illegible]	24.55	206.92	24.55	206.92	24.55	206.92	24.55	206.92
DENSITY	11.9.	.29	-74.20	.29	-46.58	.29	-69.04	.24	-65.40
SS/TUG REQUIREMENTS									
TUG PROPELLANT WT		7978.		7978.		5469.		4329.	
TUG IGN. WT.		27584.		27584.		27584.		27584.	
NUMBER OF TUGS		1		1		1		1	
NUMBER OF SS FL		1		1		1		1	

for Missions 2 and 3 of the so-called Fleming model. This output data comprises three blocks. The first block contains the mission characteristics; the second block summarizes the Tug performance by mode and compares this performance to the baseline payload definition; and the third block tabulates the Space Shuttle and Tug flight requirements by mode. Steps 1 through 10 are repeated until every mission in the model is analyzed.

Tug Cost Routine. A flow diagram of the steps comprising the Tug cost logic is presented in Figure 4-13. Initiation of this routine requires an input of the Tug type, weight, and propulsion characteristics; and the fleet size and flight activity load. If the specified Tug is an orbit injection stage and the retrieved cost data represent the stored point costs for that Tug, the routine proceeds to output the Tug cost characteristics. If the cost characteristics of a reusable Space Tug are being defined then the cost estimating relationships are exercised to evaluate each of the Tug

FLOW



STEP	SOURCE
1. RETRIEVE TUG RELATED COST DATA	DATA BANK
1A. TEST WHETHER VEHICLE IS AN ORBIT INJECTION STAGE	
2. RDT&E COST EVALUATION BY SUBSYSTEM	COST ESTIMATING RELATIONSHIPS (CERS)
3. FIRST-UNIT-COST EVALUATION BY SUBSYSTEM	CERS
4. NON-RECURRING INVESTMENT COST	CERS
5. RECURRING INVESTMENT COST	CERS
6. OPERATIONS COST	CERS
7. OUTPUT OF TUG COST SUMMARY	

Figure 4-13 Tug Cost Routine Logic

cost components. In the economic evaluation of a Tug, this cost routine is called twice. The entry point for the second call to this routine begins at step 4 and bypasses the activity-level-independent costs.

ANNEX Subroutine. The mission and payload data file, the Tug specifics from the STAR program, and the Tug user charges are inputs to the ANNEX subroutine. Given these, ANNEX computes the costs of performing the program using each proposed candidate Tug in the economically optimum way and the savings achievable by this Tug relative to a baseline orbit injection stage.

In designing ANNEX for this function, particular care was taken in developing the concept; in laying out the program flow; and in programming to preserve as many options as possible in input parameters, to make changes easy by using modular logic, and particularly to maintain maximum visibility of the internal decisions made by the program and their rationale. The program interfaces very closely with STAR and is run with it.

A flow diagram of the ANNEX program is shown in Figure 4-14. In normal use ANNEX compares a candidate Tug with a baseline Tug and computes the economic savings which the (more advanced) candidate Tug could achieve by capturing missions from the baseline Tug. An optional procedure, used to set up the baseline costs (against which the costs of the candidates are to be compared) merely computes, spreads, and discounts the costs without comparison to other systems.

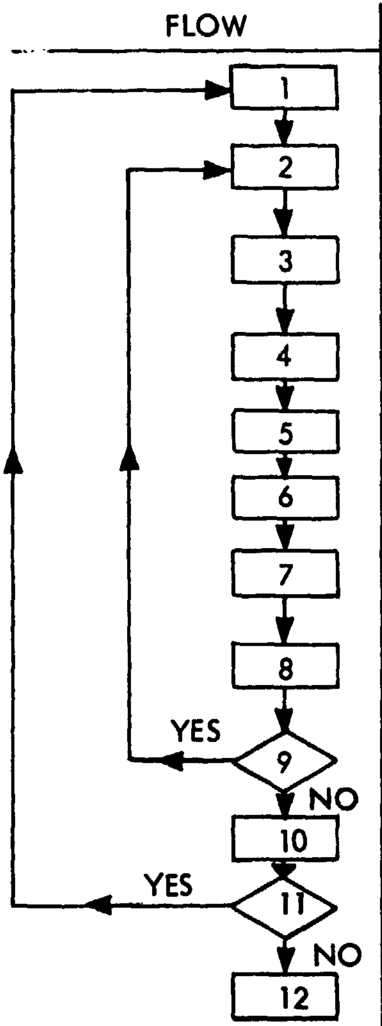
The program steps through the mission model, program by program. For each program it checks which operational modes are:

1. Permitted by the program
2. Available from the Tug

For each such mode, the program:

1. Determines the cheapest available payload option permitted by the weight capability of the Tug given the space available in the Shuttle.
2. Computes accessibility savings

ONE RUN IS MADE FOR EACH PROPOSED TUG, AS FOLLOWS:



STEP	SOURCE
1. TAKE FIRST/NEXT MISSION	MISSION MODEL
2. TAKE FIRST/NEXT APPLICABLE MODE WHICH TUG CAN PERFORM	MISSION MODEL "STAR"
3. WEIGHT CAPABILITY OF TUG IN MODE	STAR
4. COST ELEMENTS OF P/L AT WEIGHT	B/L COST FILE. L/C ALGORITHMS
5. RISK AS FUNCTION OF MODE	FACTORS/MODES
6. REFURB COST (IF P/L RETRIEVED)	ALGORITHM
7. COST SPREADS BY CATEGORY/YEAR DISCOUNTED & UNDISCOUNTED	MISSION SCHEDULE SPREAD FUNCTIONS
8. SAVINGS SPREADS	B/L COST SPREADS AND L/C COST SPREADS
9. IS THERE ANOTHER MODE FOR THIS MISSION?	
10. FLAG BEST MODE	
11. IS THERE ANOTHER MISSION?	MISSION MODEL

12. SUM COSTS & SAVINGS ACROSS MISSION MODEL
- FOR EACH MODE
- USING BEST MODE FOR EACH MISSION

PRINT OUT
- SUMMARIES FOR MISSION MODEL
- SUMMARIES BY MISSION
- PAYLOAD DATA

Figure 4-14 ANNEX Subroutine Logic

3. Computes refurbishment costs, if needed
4. Spreads all costs as required by the program schedule
5. Discounts (4)
6. Totals both (4) and (5)
7. Determines savings relative to baseline case, discounted and undiscounted. (If the candidate Tug is more expensive it does not capture this program in the mode and the savings are zero).
8. Repeats for other available modes
9. Flags mode giving best discounted savings
10. Repeats for all programs in mission
11. Sums discounted and undiscounted savings by year and for period of mission model:
    a. Using best mode for each mission
    b. Using the same mode for each mission
12. Sums Tug and Shuttle flights

An example printout option is provided in Figure 4-15 for mission Fleming number 2. The output was designed to provide program summary data to interface efficiently with the economic analysis, and to provide payload data for review of the operation of the payload effects algorithms and diagnostic data as required.

In its primary function ANNEX tests a candidate Tug against a baseline, OIS concept or family, and determines which programs the candidate Tug could perform more cheaply and how much money it would save. The program is so designed, however, that this can be done repeatedly to test concurrent families of Tugs or a series of Tugs with differing availability dates. This is done by

a. Running an evaluation of the first candidate Tug
b. Replacing the original baseline case by (a)
c. Evaluating a second Tug by overlaying it on the new baseline

This process can be repeated as often as is desired. It may be observed that each new Tug may capture programs from any of the preceding ones, not merely those in the original baseline.

*** C O S T S   A N D   S A V I N G S   B Y   M I S S I O N ***

*** TUG DEFINITION *** ** ZERO TRANSPORTATION COSTS** FULL LCW COST P/L ** COMPARED TO B/L **
TUG USER CHARGE   MODE 2   .000000 MILLION $
SHUTTLE USER CHARGE   .000000 MILLION $
DISCOUNT RATE   .10000

MISSION FLEMING NUMBER	MODE ---- (R)	FLIGHTS S/S	TUGS	COST ITEM	YEAR	UNDISCOUNTED ROTE $M	N-R INV. $M	RECUR. INV. $M	OPS DEP $M	OPS IND $M	TOTAL $M	DISCOUNTED ROTE $M	N-R INV. $M	RECUR. INV. $M	OPS DEP $M	OPS IND $M	TOTAL $M
2	2			NEW TUG													
		0	0		1972	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1973	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1974	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1975	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1976	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1977	10.060	.000	.000	.000	.000	10.060	5.163	.000	.000	.000	.000	5.163
		0	0		1978	33.762	7.557	.000	.000	.000	41.319	15.750	3.525	.000	.000	.000	19.276
		0	0		1979	20.173	11.335	.000	2.418	.000	33.926	8.555	4.807	.000	1.025	.000	14.388
		2	2		1980	3.675	3.778	.000	1.209	1.889	10.551	1.417	1.457	.000	.466	.728	4.068
		1	1		1981	12.333	.000	.000	.000	1.889	14.222	4.323	.000	.000	.000	.662	4.985
		0	0		1982	7.369	3.778	.000	.000	1.889	13.036	2.348	1.204	.000	.000	.632	4.154
		0	0		1983	3.675	3.778	.000	1.209	1.889	10.551	1.064	1.294	.000	.350	.547	3.256
		2	2		1984	12.333	.000	3.030	2.418	1.889	19.670	3.248	.000	.798	.637	.498	5.183
		4	4		1985	7.369	.000	6.060	.000	1.889	15.318	1.764	.000	1.451	.000	.452	3.667
		0	0		1986	3.675	.000	.000	1.209	1.889	6.773	.830	.000	.000	.263	.411	1.474
		2	2		1987	12.333	.000	3.030	.000	1.889	17.252	2.440	.000	.599	.000	.374	3.413
		1	1		1988	7.369	.000	3.030	.000	1.889	12.288	1.325	.000	.545	.000	.340	2.210
		0	0		1989	.000	.000	.000	2.418	1.889	4.307	.000	.000	.000	.395	.309	.704
		2	2		1990	.000	.000	.000	.000	1.889	1.889	.000	.000	.000	.000	.281	.281
		0	0		1991	.000	.000	.000	.000	1.889	1.889	.000	.000	.000	.000	.255	.255
		0	0		1992	.000	.000	.000	.000	1.889	1.889	.000	.000	.000	.000	.232	.232
		0	0		1993	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1994	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1995	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1996	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		0	0		1997	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
					TRANSPORTATION				.000						.000		
TOTAL		14	14			134.124	30.227	15.150	10.880	24.560	214.942	48.197	12.088	3.393	3.137	5.691	72.505
2	2			SAVINGS		40.567	-30.227	57.759	.440	1.752	70.490	14.294	-12.088	10.678	.184	.408	21.435

Figure 4-15   Typical ANNEX Output

DATA INTERPRETATION

Comparative analysis between the relative cost, effectiveness, and benefits of the candidate Tug systems was completed in a two step process. The first step required the integration of the data base (described in Chapter 3) with the methodology (described above) to establish the nominal characteristics of each of the candidate Tugs. In the second step the stability of these characteristics was measured through the evaluation of the sensitivity of these characteristics to changes in Tug-related parameters (internal parameters) and to perturbations in the environmental constraints within which the Tug operates (external parameters). The multidiscipline systems analysis software defined above served as the tool by which this information was generated. Results from the two steps are presented in the following paragraphs.

Comparison of Tug Concepts

The first output of the data integration and interpretation task was comparative data on the total program costs for candidate Tug concepts. Issues considered in this analysis were stage sizes, propellant combinations, vehicle configurations, expendable concepts, Tug families, and ground/space basing.

Baseline Reusable Tugs. Important variables in the relative ranking of Tug total program costs were payload savings captured, numbers of Shuttle flights, numbers of Tug flights required, and Tug fleet size. The variation in certain of these factors as Tug size is increased is illustrated in the baseline reusable Space Tug propellant combination (LO_2/LH_2). The total transportation requirements for ground-based LO_2/LH_2 Tugs as a function of propellant loading are presented in Figure 4-16; the Tug fleet-size requirements are presented in Figure 4-17, also as a function of propellant loading. Both sets of data reflect two options in Tug staging, namely tandem capability in Mode 2 (dedicated retrieval) and 4 (all-expendable) only, and tandem capability in all modes. These two cases are presented to assess the impact of increased tandem capability on the composition and level of transportation system requirements.

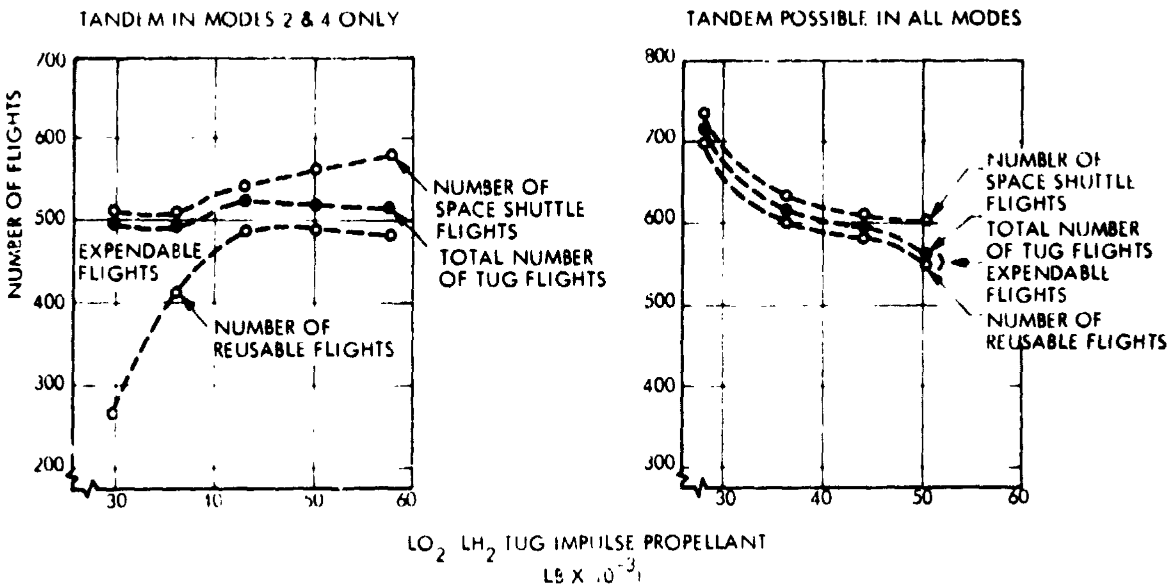


Figure 4-16 LO_2/LH_2 Tug Transportation Requirements vs Propellant Loading

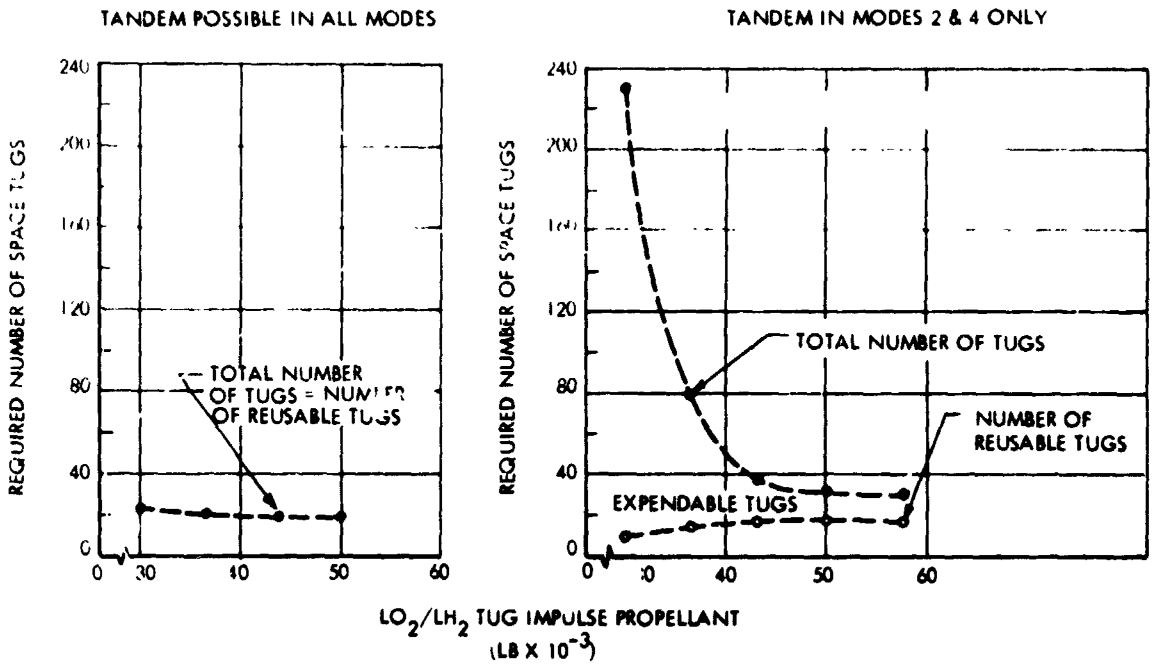


Figure 4-17 LO_2/LH_2 Tug Fleet Size vs Propellant Loading

The transportation requirements presented in Figure 4-16, comprise the numbers of Tug flights and Shuttle flights needed to perform the total mission model for the two cases of tandem mode operation. The Tug flight requirements are broken into two values, the bottom line showing numbers of reusable flights and the upper line showing total numbers of Tug flights; these curves are additive so that the difference between the lines is the number of Tug flights in the expendable mode. The upper curve plots the required number of Shuttle flights. This figure includes multiple Shuttle flights for Tug/payload combinations too big to fit in the cargo bay. The selection of a given Tug system to fly in a reusable or expendable, single or tandem mode is predicated upon minimizing discounted program costs, and therefore is significantly influenced by the payload savings obtainable for a given mission. This is demonstrated by the fact that there is significantly increased flight activity for the smaller Tugs when tandem stages are considered for all flight modes rather than for a limited number of modes only. While the number of Tug and Shuttle flights is greater in the case where tandem stages are possible in all four modes, the number of expendable Space Tug flights is significantly reduced, thereby reducing the Tug fleet size. Note that the margin of Space Shuttle flights, in excess of the total numbers of Space Tug flights, remains relatively constant for the smaller Tug propellant loadings, but that in both cases as the Tugs become larger this delta number of flights increases because of greater numbers of Tug/payload length incompatibilities.

The Tug fleet size requirements (Figure 4-17) were derived by assuming the baseline lifetime values, namely a 30-use Tug design lifetime with the Tug being flown on an expendable mission at its 30th use. These curves show the total numbers of Tugs required (top line) and the numbers of reusable Tugs in the fleet (bottom line). The difference, then, is the number of Tugs required exclusively for expendable flights; such Tugs can be built without reuse and retrieval hardware. Where tandem stages are only considered in flight Modes 2 and 4 and the Shuttle and Tug flight activity is lower the number of expendable Tugs that must be purchased drops sharply as the LO_2/LH_2 systems become increasingly capable of supporting single stage reusable missions. This fleet size approaches a constant value of 17 reusable and 14 expendable Tugs. Where tandem stages are considered in all modes, the result of minimizing discounted total program costs produces a fleet size of approximately 20 reusable and no expendable Tugs, regardless of the propellant loading. The capability to tandem in all modes is economical, especially for the smaller Tug sizes, because the increase in the number of Shuttle and Tug flights is more than offset by the payload savings captured.

When all elements comprising the total program cost are quantified – including the transportation requirements just discussed and the payloads – then plots of undiscounted total program cost versus propellant loading can be derived. Typical curves for ground-based LO_2/LH_2 Tugs are presented in Figure 4-18. These graphs, based on a Shuttle user fee of $5 million per flight, consider the same options in tandem mode operation as were considered under the transportation requirements analysis. The data points on these curves, which are additive, show that total program costs decline as propellant loading increases to about 50,000 lb, then increase slightly approaching 60,000 lb. The causes underlying this variation are discussed subseqently.

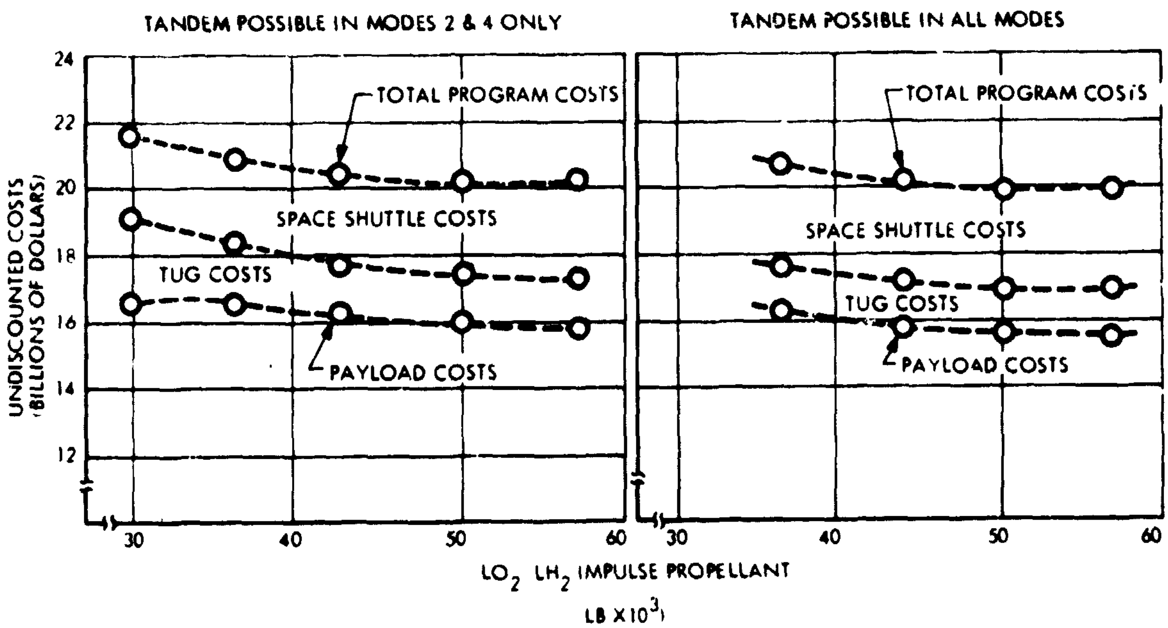


Figure 4-18 LO_2/LH_2 Tug Total Program Costs vs Propellant Loading

With respect to the magnitude of these costs, note that (1) Payload costs predominate (approximately 80 percent of total), with Shuttle costs next (approximately 12 percent), and Tug costs the least magnitude at 8 percent of the total costs; (2) the absolute difference in costs between propellant loadings is appreciable (about $1.4 billion maximum); and (3) operational sequences in which tandem stages are considered for all flight modes cost approximately $300 million less over the total mission model than the case which limits possible tandem stages to Modes 2 and 4 only.

Note that on the graphs, the circles representing discrete data points can be interpreted as the profile of a smooth continuous function, as is represented by the dashed lines. In reality, however, the actual data between the discrete points represents discontinuous step functions that result from switches in payload effects captured, flight modes, and Tug and Shuttle activity requirements. Identification of the driving factors causing these discontinuities requires a mission-by-mission examination of the optimum Tug operational mode as a function of Tug propellant weight. For Tugs with 44,000 lb, 50,200 lb, and 56,700 lb propellant loadings, the optimum mode (minimum discounted cost), the percent payload effects captured, and the Space Shuttle and Tug flight requirements are tabulated in Tables 4-5 through 4-7. These values are for tandem capability in all modes. In stepping between the 44,000 lb and 50,200 lb sizes, there are changes of values for 20 of the 64 programs in the mission model. A mission-by-mission examination of the performance and payload characteristics for these Tug sizes reveals that the following factors are causing the mode, payload effects, and Shuttle and Tug activity shifts as the size of the Tug increases:

- Tug Length. As Tug length increases, the number of missions in which payload and Tug lengths are incompatible (will not fit together in the Shuttle bay) increases.
- Payload Capability. Increased Tug size yields higher performance until the Tug total weight exceeds the Space Shuttle delivery capability.
- Alternative Operational Modes. As Tug performance increases, more demanding Tug operational modes (modes offering more Tug and/or payload reuse) are made possible.
- High-Value-Payload Reuse. As increased Tug performance permits reuse of payloads with high unit costs the benefits from payload reuse exceed the mass and volume benefits.
- Tandem vs Single Stage Tug Mode. Increased Tug performance allows some modes that require tandem Tugs to be replaced by single Tug operations.

Table 4-5 MISSION-BY-MISSION ASSESSMENT OF COST FACTORS, LO_2/LH_2 GROUND BASED TUG (W_P = 44,000 lb)

MISSION NO.	BEST MODE	% PL EFFECTS	FLIGHTS SHUTTLE	FLIGHTS TUG
2	1	100	10	10
3	1	100	12	12
4	1	100	24	24
5	3	100	11	11
7	1	100	3	3
8	3	100	2	2
9	4	100	2	2
10	2	90	3	3
11	3	100	2	2
12	3	100	2	2
21	1	100	12	12
22	1	100	12	12
23	1	100	7	7
24	3	100	2	2
25	1	100	3	3
26	3	100	6	6
27	3	100	7	7
28	3	100	14	14
29	1	50	12	12
30	1	100	12	12
31	2	90	3	3
32	1	100	3	3
33	3	100	2	2
34	3	90	2	2
35	3	100	20	20
36	3	100	10	10
37	3	100	9	9
50	3	100	4	4
51	3	100	4	4
52	3	0	1	1
53	3	0	1	1
54_1	3	0	2	1
54_2	3	0	2	1
55	4	0	2	2
56	4	100	2	2
57	4	0	2	2
58	4	50	2	2
59	4	100	1	1
60	3	100	2	2
70	3	100	11	11
71	3	100	21	21
72	2	50	38	38
73	1	100	11	11
74	3	0	5	5
75	1	100	12	12
76	2	50	21	21
77	1	100	24	24
78	2	50	11	11
80	3	100	5	5
81	3	100	8	8
82	1	50	6	6
83	1	90	12	12
84	3	100	3	3
85	3	100	4	4
86	1	90	16	16
87	2	100	20	20
88	1	100	12	12
89	1	100	12	6
90	1	100	20	10
91	1	100	24	24
92	3	0	4	4
93	1	25	36	36
94	1	25	9	9
95	2	100	32	32
TOTAL			609	591

Table 4-6 MISSION-BY-MISSION ASSESSMENT OF COST FACTORS, LO_2/LH_2 GROUND BASED TUG (W_P = 50,200 lb)

MISSION NO.	BEST MODE	% PL EFFECTS	FLIGHTS		MISSION NO.	BEST MODE	% PL EFFECTS	FLIGHTS	
			SHUTTLE	TUG				SHUTTLE	TUG
2	1	100	10	10	56	4	100	2	2
3	1	100	12	12	57	4	0	2	2
4	1	100	24	24	58	4	90	2	2
5	3	100	11	11	59	4	100	1	1
7	1	100	3	3	60	3	100	2	2
8	3	100	2	2	70	3	100	11	11
9	3	100	4	2	71	3	100	42	21
10	2	100	3	3	72	1	50	26	26
11	3	100	2	2	73	1	100	11	11
12	3	100	2	2	74	3	0	5	5
21	1	100	12	12	75	1	100	12	12
22	2	100	10	10	76	1	50	12	12
23	1	100	7	7	77	1	100	24	24
24	3	100	2	2	78	1	50	8	8
25	1	100	3	3	80	3	100	5	5
26	3	100	6	6	81	3	100	8	8
27	1	50	8	8	82	1	100	6	6
28	2	90	20	20	83	3	100	12	12
29	1	100	12	12	84	3	100	3	3
30	1	100	12	12	85	3	100	4	4
31	2	100	3	3	86	1	100	16	16
32	1	100	3	3	87	2	100	20	20
33	3	100	2	2	88	1	100	12	12
34	3	100	4	2	89	1	100	12	6
35	3	100	20	20	90	1	100	20	10
36	3	100	10	10	91	1	100	24	24
37	1	50	9	9	92	3	0	4	4
50	3	100	4	4	93	1	90	36	36
51	3	100	4	4	94	1	50	9	9
52	3	0	1	1	95	1	90	18	18
53	3	0	1	1					
54_1	3	0	2	1	TOTAL			601	558
54_2	3	0	2	1					
55	4	0	2	2					

Table 4-7 MISSION-BY-MISSION ASSESSMENT OF COST FACTORS, LO_2/LH_2 GROUND BASED TUG (W_P = 56,700 lb)

MISSION NO.	BEST MODE	% PL EFFECTS	FLIGHTS SHUTTLE	FLIGHTS TUG	MISSION NO.	BEST MODE	% PL EFFECTS	FLIGHTS SHUTTLE	FLIGHTS TUG
2	1	100	10	10	56	4	100	2	2
3	1	100	12	12	57	4	0	2	2
4	1	90	24	24	58	4	100	2	2
5	3	100	11	11	59	4	100	1	1
7	1	100	3	3	60	3	100	2	2
8	3	100	2	2	70	1	25	11	11
9	3	100	4	2	71	3	100	42	21
10	2	100	3	3	72	1	90	26	26
11	3	100	2	2	73	1	100	11	11
12	3	100	2	2	74	3	0	5	5
21	1	100	12	12	75	1	100	12	12
22	1	90	6	6	76	1	90	12	12
23	1	100	7	7	77	1	100	24	24
24	3	100	2	2	78	1	90	8	8
25	1	100	3	3	80	3	100	5	5
26	3	100	6	6	81	3	100	8	8
27	1	90	8	8	82	1	100	6	6
28	2	100	20	20	83	3	100	12	12
29	1	100	12	12	84	3	100	3	3
30	1	100	12	12	85	3	100	4	4
31	1	100	3	3	86	1	100	24	16
32	1	100	3	3	87	1	100	24	12
33	3	100	2	2	88	1	100	12	12
34	3	100	4	2	89	1	100	12	6
35	3	100	20	20	90	1	100	20	10
36	2	50	15	15	91	1	100	24	24
37	1	90	9	9	92	3	0	4	4
50	3	100	4	4	93	1	90	36	36
51	3	100	6	4	94	1	90	9	9
52	3	0	1	1	95	1	100	18	18
53	3	0	1	1					
54_1	3	0	2	1		TOTAL		616	551
54_2	3	0	2	1					
55	4	0	2	2					

- Tug Offloading. When the Tug weight exceeds the Shuttle delivery capability, an increase in Tug size results in a decrease in Tug performance because of the necessity to further offload the larger Tug.

A summary of the effect that each of these factors has on the 20 missions that shift is tabulated in Table 4-8. In increasing the propellant weight from 44,000 lb to 50,200 lb only three missions accrue cost penalties, while the remaining 17 yield cost benefits. Out of the 20 missions that change, three have a decrease in the percentage of mass and volume benefits captured. In missions 27, 28, and 37 the operational mode is shifting from an expendable to a reusable mode. These shifts result in a decrease in mass and volume benefits, but yield net gain in payload benefits because of the cost savings associated with payload reuse. In mission 83 the opposite effect occurs. The additional stage inert weight further degrades the Tug performance for this mission and forces Tug operations from a reusable to an expendable mode. Although there is an increase in the mass and volume benefits, the loss of payload reusability results in a net increase in payload cost.

In stepping between propellant weights of 50,200 lb and 56,700 lb, changes occur in 17 of the 64 missions. These changes are all caused by the same factors (see Table 4-8). The increased Tug size at 57,000 lb propellant loading results in cost savings for three missions (36, 70, and 72) and results in cost increases for four missions (4, 51, 86, and 87). The remaining ten missions benefit from the increased Tug size through increased payload capability.

Because the above, defined cause and effect relationships are discrete the total program cost curve as a function of propellant weight is a piecewise continuous function. For each continuous portion of the curve the payload costs remain constant and the Tug related costs increase. However, analysis of each of these individual discontinuities was outside the scope of this study.

One other aspect of the baseline LO_2/LH_2 Tug cost comparison that was investigated on the study was the relative magnitude of the individual classes of payload cost savings. The three components of payload cost savings for a Space Tug system are weight-and-volume relaxation; payload reusability; and payload accessibility in case of failure.

Table 4-8 CHANGES IN TUG/PAYLOAD COST FACTORS WITH INCREASING PROPELLANT WEIGHT

	MISSION NO.	INCREASED TUG LENGTH	INCREASED PAYLOAD CAPABILITY	ALTERNATE MODE POSSIBLE	REUSABILITY OF PAYLOAD	SINGLE TUG REPLACES TANDEM TUG	INCREASE IN TUG OFFLOADING
TUG PROPELLANT WEIGHT VARIATION: 44,000 TO 50,200 LB	9	X	X				
	10		X				
	22					X	
	27				X	X	
	28			X	X		
	29		X				
	31		X				
	34		X				
	37				X	X	
	58		X				
	71	X					
	72		X			X	
	76		X			X	
	78		X			X	
	82		X				
	83						X
	86		X				
	93		X				
	94		X				
	95		X	X			
TUG PROPELLANT WEIGHT VARIATION: 50,200 TO 56,700 LB	4						X
	22		X				
	27		X				
	28		X				
	31		X				
	36		X		X		
	37		X				
	51	X					
	58		X				
	70				X		
	72		X				
	76		X				
	78		X				
	86	X					
	87	X					X
	94		X				
	95		X				

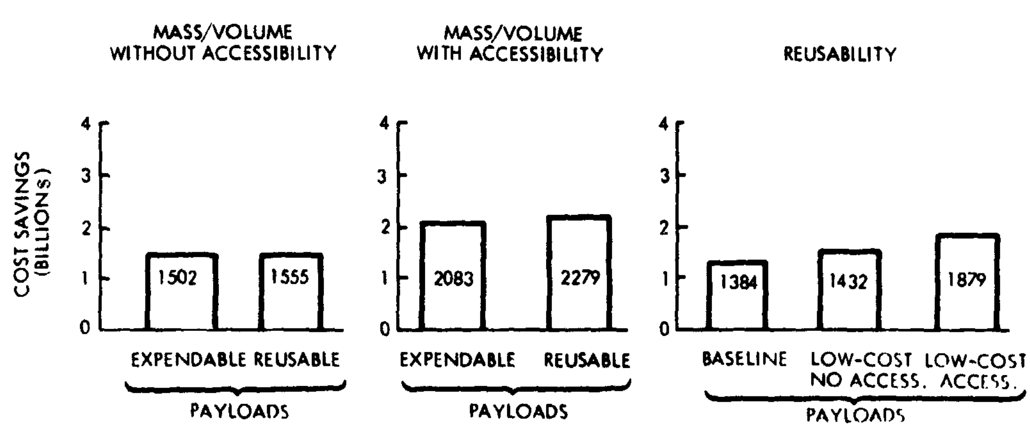
The contribution of each of these items to the payload savings for the 50,200 lb LO_2/LH_2 stage was determined by evaluating total program costs for each level of payload effects. The results are presented in Table 4-9. Of the total payload cost savings of $3.962 billion undiscounted (difference between baseline expendable and low cost reusable with accessibility) $1.384 billion is from reusability, $1.55 billion from mass and volume, and $1.028 from accessibility.

The transportation costs are relatively insensitive for the expendable payloads because of the large payload placement capability of this Tug configuration across the mission model velocity requirements. However, payload reusability does affect the Tug fleet size and the number of Shuttle flights, and results in as much as a $402 million increase in transportation costs. It is interesting to note that a $402 million added investment in transportation costs yields $4.364 billion in payload savings.

Table 4-9 RELATIVE CONTRIBUTION OF PAYLOAD COST SAVINGS

LO_2/LH_2 SPACE TUG (W_P = 50,158 LB) TANDEM CONFIGURATIONS ALLOWED IN ALL MODES

	COST ($MILLIONS)			
PAYLOAD DEFINITION	PAYLOADS	TUGS	SHUTTLES	TOTAL
BASELINE EXPENDABLE	19,927	1343	2670	23,940
LOW COST EXPENDABLE (NO ACCESS.)	18,378	1390	2670	22,438
LOW COST EXPENDABLE (ACCESS.)	17,797	1390	2670	21,857
BASELINE REUSABLE	18,249	1382	2925	22,556
LOW COST REUSABLE (NO ACCESS.)	16,625	1402	2975	21,006
LOW COST REUSABLE (ACCESS.)	15,563	1410	3005	19,978



The cost savings from mass/volume with and without accessibility are relatively insensitive to payload reusability as is evident from the two bar graphs.

Reusable Tugs With Alternative Propellant Combinations. Having established the total program cost trends for reusable ground-based LO_2/LH_2 Tugs it is appropriate, next, to consider the other candidate propellant combinations. In Figure 4-19, the undiscounted total-program costs for Tugs using LF_2/LH_2 and $FLOX/CH_4$ propellants are plotted on a common scale with the LO_2/LH_2 costs just presented (all values are for tandem capability in Modes 2 and 4, only). These curves were built up from the same type of transportation and fleet-inventory requirements analyses as were the curves for the LO_2/LH_2 values

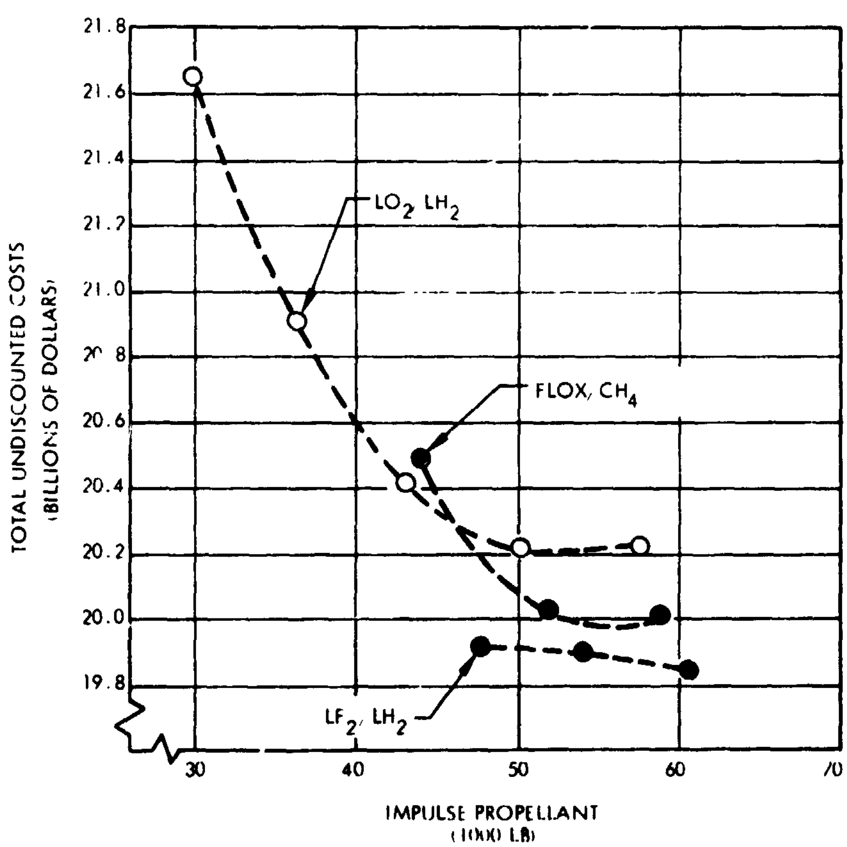


Figure 4-19 Reusable Space Tug Cost Comparison by Propellant Combination

Both the LO_2/LH_2 and $FLOX/CH_4$ Tugs exhibit a tendency to reach apparent optimum propellant loadings, whereas the LF_2/LH_2 Tugs appear to be relatively insensitive over the range examined. This insensitivity results from the high performance capability of LF_2/LH_2 Tugs that allows these Tugs to capture a large percentage of the available payload benefits (89 percent for a 47,800 lb propellant load and 94 percent for 60,600 lb propellant weight).

The efficiency of the $FLOX/CH_4$ and LF_2/LH_2 Tugs results in a \$200 to \$300 million undiscounted savings over the optimum LO_2/LH_2 Tug. For the $FLOX/CH_4$ Tug this cost savings is primarily a result of the smaller Tug RDT&E and first-unit costs and the smaller number of Space Shuttle flight requirements because of the lesser numbers of payload-Tug length incompatibilities. For the LF_2/LH_2 Tugs, the primary cost savings result from the ability to capture a larger portion of the available payload benefits. Although the undiscounted-cost comparison slightly favors LF_2/LH_2 Tugs over $FLOX/CH_4$ configurations, the cost differences disappear when expenditures are discounted at 10 percent. This is because the $FLOX/CH_4$ costs are lower in the early time period (i.e. RDT&E, fleet buy) and are higher in the time period when discounting effects are greatest.

An important side issue in the comparison of reusable Tug propellant combinations is the relationship between performance and (economically) optimum stage size. Figure 4-20 depicts the changing payload capability as a function of the LO_2/LH_2 Space Tug design propellant weight for a synchronous equatorial mission in two orbital flight operational modes (roundtrip payload and payload placement/recoverable Tug). Increasing payload capability as propellant weight increases is eventually interrupted by the Space Shuttle delivery capability. From that point on, larger stages must be off-loaded, thereby decreasing payload capability. The peaks of the two curves occur at approximately 51,600 and 57,600 lb of propellant. The chart also shows the effect on payload weight for the alternative mode of selecting the peak size on one of the curves. The sensitivity of the roundtrip curve (Mode 1) over this range of propellants is nearly 500 lb and is approximately half the differential in payload weight for the expendable-spacecraft/reusable-Tug mode (Mode 3) over the same propellant range. Because the

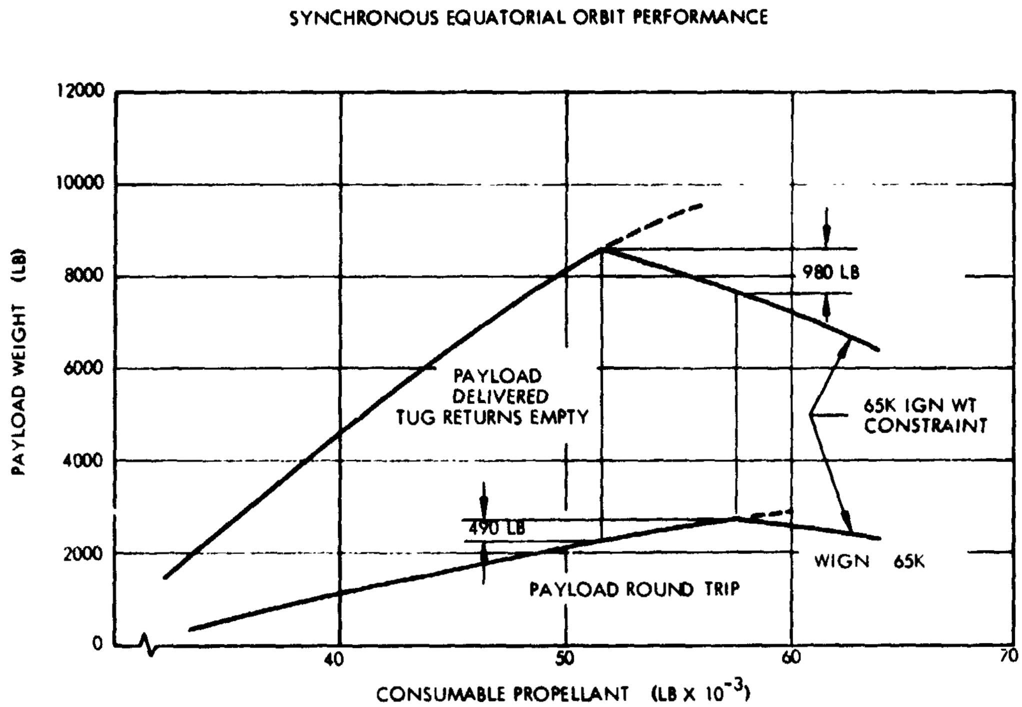


Figure 4-20 Synchronous Equatorial Orbit Performance For LO_2/LH_2 Space Tug

minimum total program costs for LO_2/LH_2 systems came out in the low 50,000 lb propellant weight category, it can be said that, for the study groundrules, a LO_2/LH_2 stage design should be closer to maximizing payload capability for a synchronous equatorial mission in Mode 3 than in Mode 1.

Similar charts for the LF_2/LH_2 and $FLOX/CH_4$ propellants are presented in Figures 4-21 and 4-22 respectively.

For the LF_2/LH_2 case, the Δweight over the range of propellants determined by the peaks of both curves (approximately 6700 lb) is greater for the roundtrip mode than it is for the expendable spacecraft/reusable Tug mode. From a total program cost standpoint, the LF_2/LH_2 systems were relatively insensitive to propellant loading but do

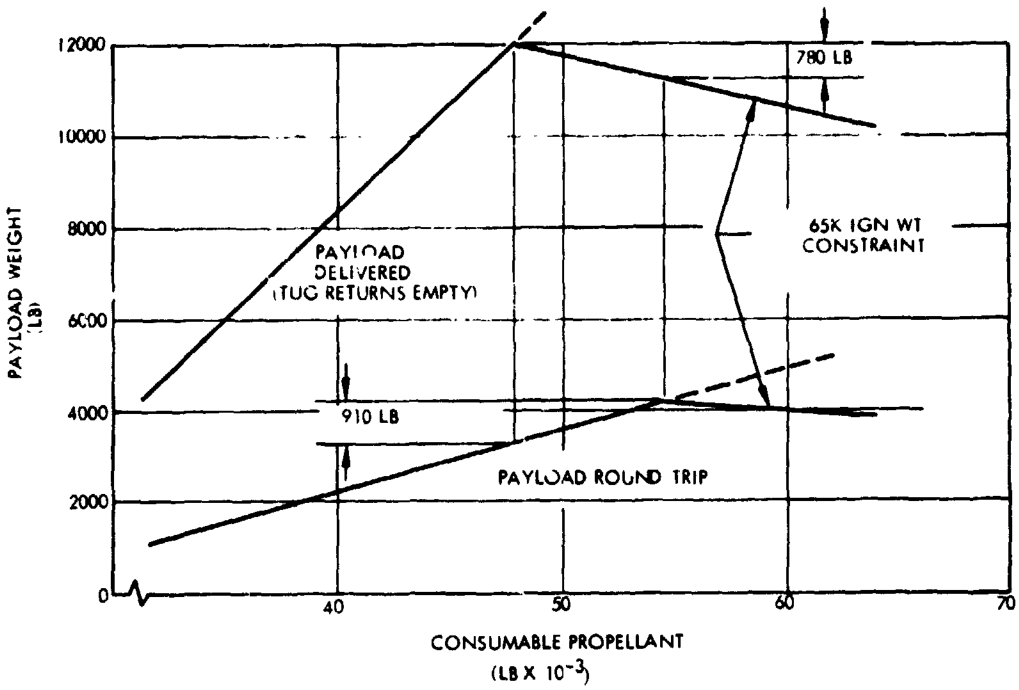


Figure 4-21 Synchronous Equatorial Orbit Performance LF_2/LH_2 Space Tug

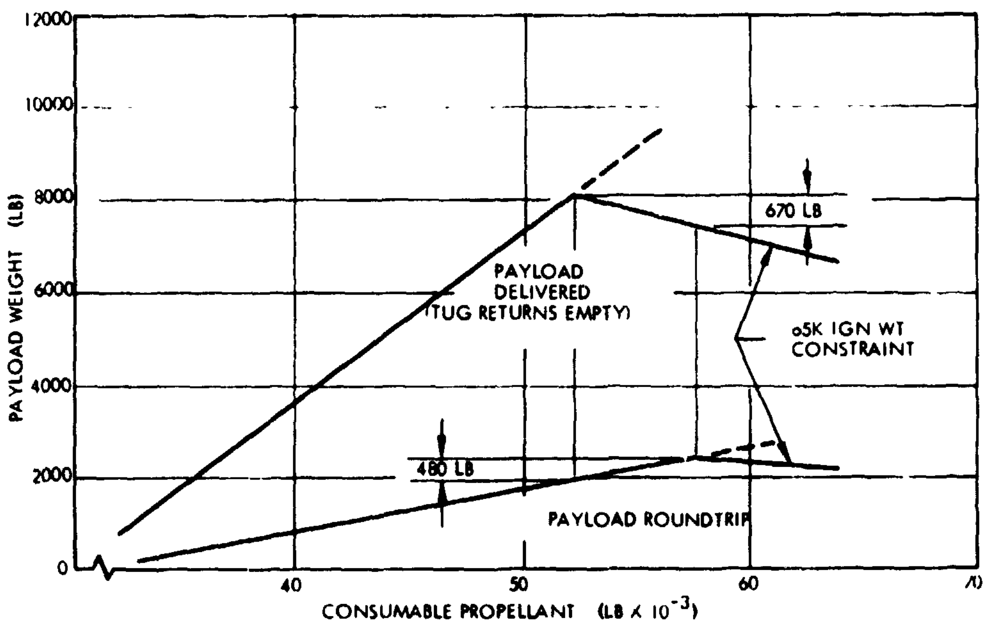


Figure 4-22 Synchronous Equatorial Orbit Performance For $FLOX/CH_4$ Space Tug

show a trend that found the larger stages examined to be more cost effective. This trend, in conjunction with the data on the facing page and the entire study groundrules, indicates that a LF_2/LH_2 Space Tug design should be closer to maximizing payload capability in Mode 1 (round trip payload) than Mode 3 (expendable spacecraft/reusable Tug) for a synchronous equatorial mission. For the FLOX/CH_4 design Space Tug as defined for this study, the relationship between Tug size and the peaks of the performance curves for a synchronous equatorial mission in the two orbital flight operational modes produces the smallest Δ propellant of the three propellant combinations examined (approximately 5300 lb). Also, even though the Δ payload capability is smaller for the roundtrip spacecraft sequence (Mode 1) as compared to the Δ weight over the same propellant spread for the expendable-spacecraft/reusable-Tug sequence (Mode 3), the relative magnitudes of the differences are not significant. The optimum Tug size from a total program cost standpoint tends to be in the mid-50,000 lb propellant range, or between the peaks of the performance curves for Modes 1 and 3 for a synchronous equatorial mission.

Stage-and-One-Half Tugs. Having compared various propellant combinations in single-stage Tug configurations, the next concept to be considered was the stage-and-one-half configurations in which expendable tankage was used with a reusable core stage. The undiscounted total program costs for stage-and-one-half LO_2/LH_2 Tug configurations are compared against single stage LO_2/LH_2 Tug costs in Figure 4-23. Important ground rules assumed for the stage-and-one-half concepts were as follows:

- The stage-and-one-half system was based on a reusable LO_2/LH_2 core stage with a 30,000 lb propellant loading; the core stage was 15 ft in diameter and represented the approximate lower limit of LO_2/LH_2 stage designs that still support the entire mission model.
- The drop tank set was defined as a single LH_2 tank with multiple clustered LO_2 tanks. The tank set was also 15 ft in diameter and was assumed to be mated to the core stage for purposes of launch in the Space Shuttle.
- The orbital flight sequence was defined so that tank set would be jettisoned at the target along with the payload, rather than when the tanks are depleted. This assumption means a decrease in performance capability compared with jettisoning the tanks at depletion but was made to circumvent the operational problems of ending a burn sequence prior to completing a total maneuver.

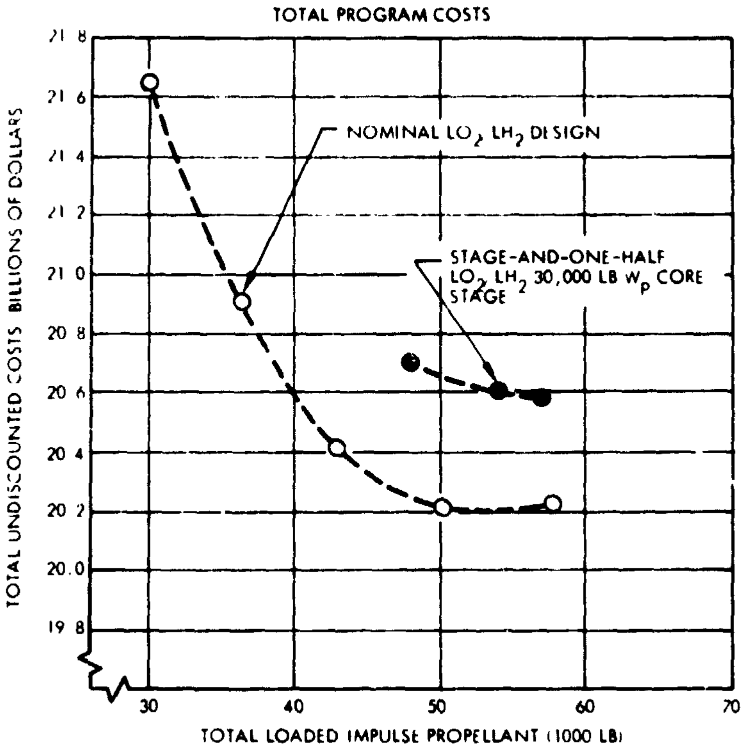


Figure 4-23 Stage-and-one-half LO_2/LH_2 Space Tug Costs

The three data points shown in Figure 4-23 represent the total stage-and-one-half propellant load (i.e., a 30,000 lb W_p core stage in combination with 18,000 lb, 24,000 lb, and 27,000 lb W_p drop tank capacities). The 18,000, 24,000, and 27,000 lb loadings represent the largest capacities for 2, 3, and 4 clustered LO_2 tanks within the design estimating relationships used for the drop tanks. As was expected, the addition of the drop tank precluded the selection of tandem core stages for any of the missions in the model. The total cost figures shown do represent, however, a mix of using the core stage alone or in combination with the tank set based upon the minimum cost to support an individual program. Note that a 30,000 lb propellant stage, when used with a 27,000 lb drop tank set, saves over $1.0 billion compared to using a single or tandem 30,000 lb stage without drop tanks. While the minimum differential with respect to a single large LO_2/LH_2 reusable Space Tug is approximately $400 million over the 12-year mission model, variations in operational modes and core and tank set sizes could potentially reduce this figure.

Expendable Orbit Injection Stages. The comparison of Tug concepts then proceeded from the partially expendable stage-and-one-half concepts to the fully expendable orbit injection stages. Figure 4-24 compares the undiscounted total program costs of four OIS concepts (three stages and a best mix family of Agena and Centaur) against the costs for typical reusable Tugs (LO_2/LH_2, tandem capability in Modes 2 and 4 only). The orbit injection stages, applicable to Mode 4 only, were evaluated on the basis of either single or tandem stages for every mission. For the expendable systems shown, nearly 100 percent of the low-cost payload savings associated with the expendable spacecraft were captured by all the vehicles. Transportation costs, therefore, account for the major differences among the various expendable orbit injection stages. The transportation costs are reflected in the numbers of Space Shuttle flights required (primarily a function of the OIS length), and in the user fee of the candidate systems. Although, on an undiscounted dollar basis the best expendables (the Agena/Centaur mix and the Large Tank Agena) are from \$300 million to \$600 million more expensive than the 30,000 lb W_P LO_2/LH_2 reusable system, on the basis of a 10 percent discount rate

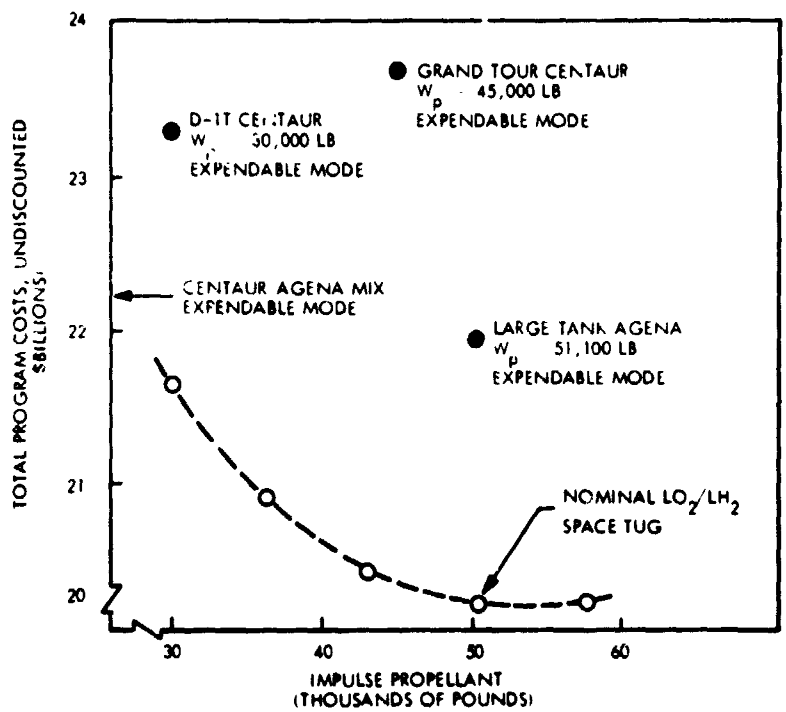


Figure 4-24 Expandable/Reusable Tug Cost Comparison

these same systems save from \$20 million to \$350 million with respect to the same 30,000 lb LO_2/LH_2 system. On this basis, the improper selection of a reusable Tug size can result in a system less economical than an all-expendable orbit injection stage system. As defined for the purposes of this study the most cost-effective OIS is the Large Tank Agena which is approximately \$1.7 billion undiscounted, or \$220 million discounted, more expensive than the best reusable LO_2/LH_2 system.

A separate comparison of orbit injection stages and reusable Tugs was performed to determine whether the transportation cost savings alone could justify development of the reusable Tug. Table 4-10 displays the categories and total transportation costs for two reusable stage LO_2/LH_2 designs, the Agena/Centaur mix, and Large Tank Agena systems. In this comparison, payloads were defined to be expendable but subject to low cost payload effects. The 48,500 lb propellant LO_2/LH_2 system was added for comparison because this Tug is 6 in. shorter than the 50,200 lb system and therefore

Table 4-10 TRANSPORTATION COST COMPARISON

LOW COST EXPENDABLE PAYLOADS

TUG CONCEPT	NO. OF SHUTTLE FLIGHTS	NO. OF EXPENDABLE TUG FLIGHTS	NO. OF REUSABLE TUG FLIGHTS	NO. OF EXPENDABLE TUGS	NO. OF REUSABLE TUGS
LO_2/LH_2 W_p = 50,200	534	28	465	12	16
LO_2/LH_2 W_p - 48,500	516	21	479	5	16
AGENA/CENTAUR	507	378/116	-	378/116	-
LARGE TANK AGENA W_p 50,900	499	485	-	485	-

UNDISCOUNTED COST ($MILLIONS)

TUG CONCEPT	INVESTMENT			OPERATIONS		TOTAL
	RDT&E	RECURRING	NONRECURRING	ACTIV. DEPENDENT	ACTIV. INDEP.	
LO_2/LH_2 W_p 50,200	528.	321.	101.	3028.	82.0	4060.
LO_2/LH_2 W_p 48,500	526.	327.	43.	2946.	82.0	3924.
AGENA/CENTAUR	105.4	0	1406.	2932.	0	4443.
LARGE TANK AGENA W_p 50,900	51.5	0	1255.	2826.	0	4133.

allows single Shuttle launch compatibility with several 25 ft payloads that require separate Shuttle launches for Tug and payload with the longer 50,200 lb configuration. The evaluation of the 48,500 lb LO_2/LH_2 Tug points up the discontinuous nature of the smooth functions represented by the dashed lines where total program costs are displayed in the charts.

The upper table presents the fleet size and Shuttle and Tug activity level requirements. The lower table provides undiscounted dollar costs for the development, manufacture, use, and support of the Tugs, and includes (under operations-dependent costs) the user fee of $5 million times the number of Space Shuttle launches required for each system. A comparison of the total transportation costs shows that even though the reusable Tug systems are cheaper, on an undiscounted cost basis, there is only a five percent differential, under the above stated groundrules, between the best OIS and the best LO_2/LH_2 reusable Space Tug design and that this five percent comes about because of variations in all the five major cost categories. When the costs are compared at a 10 percent discount, the rankings reverse and the OIS is about $150 million less expensive than the 48,500 lb LO_2/LH_2 Tug.

An additional comparison of Space Tug total program costs as a function of stage length is presented in Figure 4-25 with costs plotted in undiscounted dollars. Considering the relative propellant densities of the various cryogenic Space Tug systems, along with the fact that the $FLOX/CH_4$ and LF_2/LH_2 data points are for total loadings in the same category as the two or three largest LO_2/LH_2 systems, the trend of reduced program cost for shorter stage length is clearly evident. Moving from the least cost LO_2/LH_2 data point at 50,200 lb W_P to a LF_2/LH_2 system reduces total program costs by increasing performance capability and by reducing stage length up to 17 percent. This is equivalent to an increase in the amount of the cargo bay available to accommodate payloads of up to 10 percent. The savings associated with the least expensive nominal design $FLOX/CH_4$ vehicle, that has performance lower than the 50,200 lb W_P LO_2/LH_2 system, comes totally from its ability to provide approximately 17 percent more Shuttle Cargo bay length for spacecraft accommodation. With respect to the least cost LO_2/LH_2 system the LTA affords a reduction of nearly 12 ft in stage length. Because the LTA

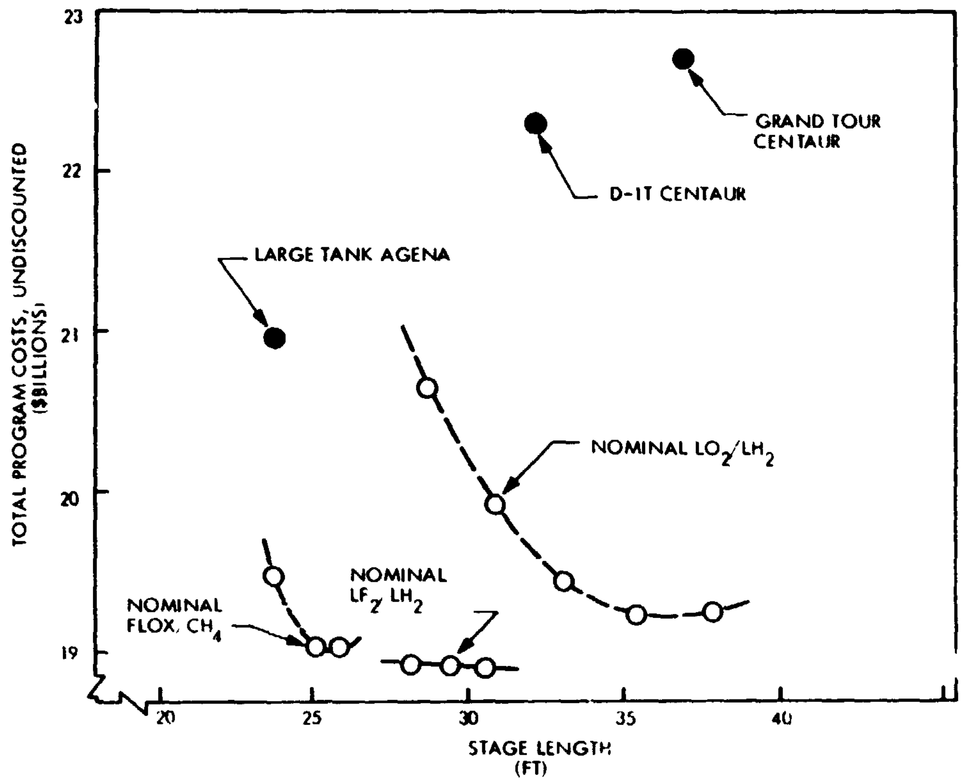


Figure 4-25 Total Program Cost – Stage Length Comparison

provides approximately 36 ft of cargo bay for the payload and because average spacecraft length for this model is approximately 12 ft, the LTA affords (for at least 50 percent of the programs, holding weight constant) a tripling of the payload length without impacting Shuttle transportation requirements.

Tug Families. After considering various ground-based Tug concepts individually, the feasibility of grouping Tugs into families was explored. Four categories of Tug families, each capable of performing the entire mission model, were considered: (1) a small and a large reusable LO_2/LH_2 system with shared development costs; (2) a small LO_2/LH_2 reusable design plus an expendable tank set; (3) a small LO_2/LH_2 reusable vehicle plus an orbit injection stage; and (4) an orbit injection stage and a large reusable LO_2/LH_2 Tug with an IOC date of 1985. For the first three cases it was assumed that these familes would be developed so both vehicles would be available at the beginning of the mission model.

Table 4-11 shows the family descriptions and the computed program costs, in undiscounted dollars, for the first three families. A common small LO_2/LH_2 reusable stage size, for all three categories, was defined as having a 20,000 lb propellant capacity in order to provide maximum differential in performance and size, thereby generating the greatest interaction with the other family member(s). These other members as shown were the 50,200 lb LO_2/LH_2 reusable Tug, a drop tank with the same 20,000 lb propellant capacity as the core stage, and the LTA orbit injection stage. Note that the figures for the 20,000 lb W_P LO_2/LH_2 reusable design reflect the fact that this system cannot perform, even in a tandem stage mode, one of the high weight interplanetary missions, but that in every case where a mix is defined the total mission model can be performed. The total program costs that should be compared, therefore, are those shown for the best single LO_2/LH_2 system ($19,978 million undiscounted) the best OIS ($21,947 million undiscounted), and the values associated with each mix. The results

Table 4-11 SPACE TUG FAMILY ANALYSIS

CANDIDATE TUG	NUMBER OF TUGS*	COSTS ($ MILLIONS, UNDISCOUNTED)						
		RDT&E	INVESTMENT		OPERATIONS		PAYLOADS	TOTAL PROGRAM
			NON-RECURRING	RECURRING	ACTIVITY DEP.	ACTIVITY INDEP.		
LO_2/LH_2** W_P = 20,000 LB	54	487.	434	204.	4147.	82.	16,277	21,631.
LO_2/LH_2 W_P = 50,158 LB	19	528.	386.	0	3419.	82.	15,563.	19,978.
MIX	6/12	647.	363.	0	3350.	82.	15,592.	20,034.
LO_2/LH_2** W_P = 20,000 LB	54	487.	434.	204.	4147.	82.	16,277.	21,631.
MIX: STG + 1/2 LO_2/LH_2 (CORE W_P = 20,000 LB + DROP TANK W_P = 20,000 LB)	26/302	533.	304.	104.	3321.	82.	16,131.	20,475.
LO_2/LH_2** W_P 20,000 LB	54	487.	434.	204.	4147.	82.	16,277.	21,631.
LTA W_P 50,900	485	52.	0	1255.	2826.	0	17,814.	21,947.
MIX	14/219	539.	281.	566.	3144.	82.	16,479.	21,091.

*REUSABLE TUGS/EXPENDABLE TUGS (OR TANK SETS)
**MISSION 58 CANNOT BE PERFORMED WITH THIS TUG

of this analysis show that even with only a 22.5 percent increase in RDT&E (over the costs of a single large cryogenic stage) for the all-reusable family, there is minimal economic benefit associated with this mix. The relative interaction of the family elements is based upon using the Tug design that minimizes individual program costs on a program-by-program basis. The stage-and-one-half family shows an increase in total program costs of 2.5 percent with respect to the best single stage LO_2/LH_2 data point at 50,200 lb W_P but is actually less costly on the basis of transportation costs alone. The introduction of a small reusable cryogenic system with an efficient OIS reduces total program costs with respect to the expendable vehicle alone by over $800 million even with separate, additive development costs; however this family is 6 percent more costly than the 50,200 lb W_P reusable LO_2/LH_2 system alone. If the families are compared on a discounted cost basis rather than on undiscounted costs, there is one switch in the rankings caused when the all-reusable family becomes more costly (by two percent) than the single large reusable Tug; however, the difference is too small to be considered decisive.

For the final family it was assumed that an orbit injection stage would perform all the the payload placements through 1984 and that the reusable Tug would completely supersede the OIS for missions performed after 1984. Payloads that were scheduled for launch before 1985 but that could be retrieved by the reusable Tug were sized and costed as reusable payloads launched by an OIS. A summary of the characteristics of this mix are presented in Table 4-12. These results indicate that the penalty for 1985 introduction of the reusable Tug is $773 million undiscounted, but only about $88 million discounted. This small discounted differential is a result of delaying the development and investment costs of the LO_2/LH_2 system by six years. The resulting funding distributions, in terms of total program cost, for the 1979 and 1985 introduction of the 50,200 lb LO_2/LH_2 reusable Tug are compared in Figure 4-26.

Table 4-12

PHASED SPACE TUG FAMILY ANALYSIS
(All Costs in $ Millions)

Candidate Tug	Number of Tugs	Number of Shuttle Flights	Transportation Costs Tug	Transportation Costs Space Shuttle	Payload Cost	Total Program Cost Undis-counted	Total Program Cost Dis-counted
LO_2/LH_2 W_p = 50160 LB IOC = 1979	19	601	1,410	3,005	15,563	19,978	6,609
LTA W_p = 50900 IOC = 1979	485	499	1,648	2,495	17,814	21,947	6,941
LO_2/LH_2 IOC - 1985 LTA 1979 - 1984	10/243	321/249 (570)	1,018/847 (1,865)	1,605/1,245 (2,850)	16,036	20,751	6,697

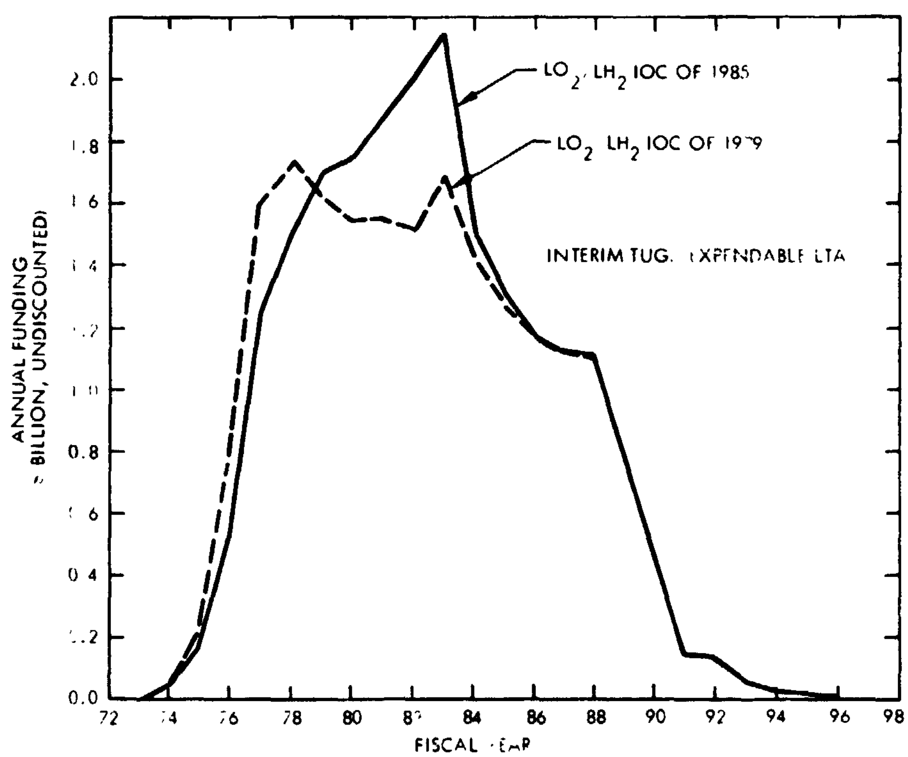


Figure 4-26 **Annual Funding Requirement for a Delay of Six Years in LO_2/LH_2 IOC (Total Program Costs: Tug, Shuttle, and Payloads)**

Space Based Tug Systems. The final element in the Tug concept comparison was an evaluation of space basing. Since the space basing of reusable Tugs is a complex operational problem, the emphasis in this analysis was on bounding parametrically the magnitude of potential costs and cost savings attainable with this basing mode. No definitive estimate of these costs can be derived until the operational efficiency of the space-based Tug and its logistics system are well defined.

Important procedures and assumptions used for the space-basing analysis, only, were as follows:

- The analysis was split into two elements, namely (1) Tug operations and (2) logistics system operations
- It was assumed that the logistics problem (e.g., resupply of Tug propellants and payloads) could be treated on an annual basis rather than mission-by-mission
- Tug operations were grouped by launch azimuth because of the large plane-change penalties associated with a single Tug operating azimuth
- The space-based Tug concept was selected as a 50,200 lb LO_2/LH_2 configuration. Sizing optimization was not addressed in the analysis
- Space-based Tugs were assumed to receive, at resupply, only the propellants needed for the next mission; however, Tugs delivered to orbit for initial placement or recycling were considered to be fully loaded
- Resupply propellants were assumed to be delivered by a Space Shuttle containing cryogenic tankage (inert weight 2000 lb) in its cargo bay. The amount of propellant carried was constrained by the Shuttle payload capacity, less this tankage weight. Transfer and chilldown losses were assumed to be one percent for LO_2 and two percent for LH_2. Propellants were delivered directly to empty Tugs rather than to an orbiting propellant depot
- Payloads were assumed to be delivered in clusters by the Shuttle (up to 5 per Shuttle)
- Tug lifetime was assumed to be 30 uses, total; however, each Tug was returned to earth after 10 flights or two months on orbit.

Using these assumptions, three space-basing cases were analyzed. The Space Tug design in the first case reflects a structural modification for space basing (approximately +180 lb structural weight beyond the same size ground-based system) and a selection of operational modes based upon attaining maximum payload effects (minimum payload costs). The second case was dictated to have the same payload costs as the same size ground-based Tug system provided. This meant that the Tug design and orbital flight modes would also be identical with the comparable ground-based system, thereby isolating the transportation effects. The third case was added to explore uncertainties in the level of redundancy and autonomy for space-based Tug avionics. It used the space-basing design estimating relationships plus an arbitrary increase of 50 percent in the baseline avionics weights. With the contingency factor and related impact on structures weight, this perturbation amounted to a total vehicle weight increase of about 420 lb above case 1. The amount of payload effects captured and the associated flight modes were determined by minimizing total program cost on an individual mission-by-mission basis flying this new Tug configuration in a ground-based mode and then applying the transportation groundrules for space basing.

The groundrules for space basing reflect the concept of minimizing the Space Shuttle support requirements for a constant mission model. This is accomplished by (1) not having to deliver and return the Space Tug to earth on every Space Shuttle trip, (2) using only the Space Tug propellant required to support an individual mission, (3) periodic delivery of the maximum Space Shuttle payload capability in terms of Tug propellant weight, and (4) the Space Shuttle delivery of multiple payloads. Table 4-13 illustrates the typical payload delivery activity for one year of the mission model. The payload groupings were determined on the basis of missions to be supported for a given year at an individual inclination angle category. These missions were then combined to use most efficiently the Space Shuttle delivery and cargo bay size limitations. Note that, as shown in this table, the length constraint was generally the limiting factor for due-east launches, while for the higher inclinations both total weight and geometry served to define the required Space Shuttle activity to transport payloads. Note also that because of study limitations no attempt was made to evaluate adapter weights or dimensions among the various grouped payloads.

The distribution of Space Shuttle flights in terms of inclination angle categories, required to support the first space-basing case is presented in Figure 4-27. The total number of flights is 535 or 27 less than the ground-based Tug (tandem possible in Modes 2 and 4 only) or 66 less when tandem stages were considered for all modes. Of the total 535 flights, 72 percent support the due-east launch from ETR category with the remaining 28 percent reflecting WTR requirements. The average number of flights at ETR is 32 per year with a maximum of 38 occurring in 1988 and a minimum of 28 in the years 1982, 1985, and 1989. The maximum number of polar flights is 12 in 1985, with anywhere from 1 to 3 flights per year in the 99 to 100 degree range, and 1 or 2 per year for the 63.4 degree category.

Table 4-13 TYPICAL PAYLOAD GROUPINGS FOR SPACE BASING

INITIAL INCLINATION 28.5° SPACE BASED CASE 1 YEAR = 1981

SPACE SHUTTLES		PAYLOADS 1	2	3	4	5	TOTALS
1	LENGTH = WEIGHT =	25 9280	15 4905	12 2872	8 2199		60 19,256
2	LENGTH = WEIGHT	25 9280	15 4905	12 2872	8 2199		60 19,256
3	LENGTH = WEIGHT =	22 3921	17 5441	12 2872	8 1233		59 13,467
4	LENGTH WEIGHT =	24 7803	21 11973	6 2835	5 1083	4 2394	60 26,088
5	LENGTH = WEIGHT =	25 7271	12 2872	12 1904	8 2916		57 14,963
6	LENGTH = WEIGHT =	12 2872	12 2872	12 9499	8 2255	6 1417	50 18,915

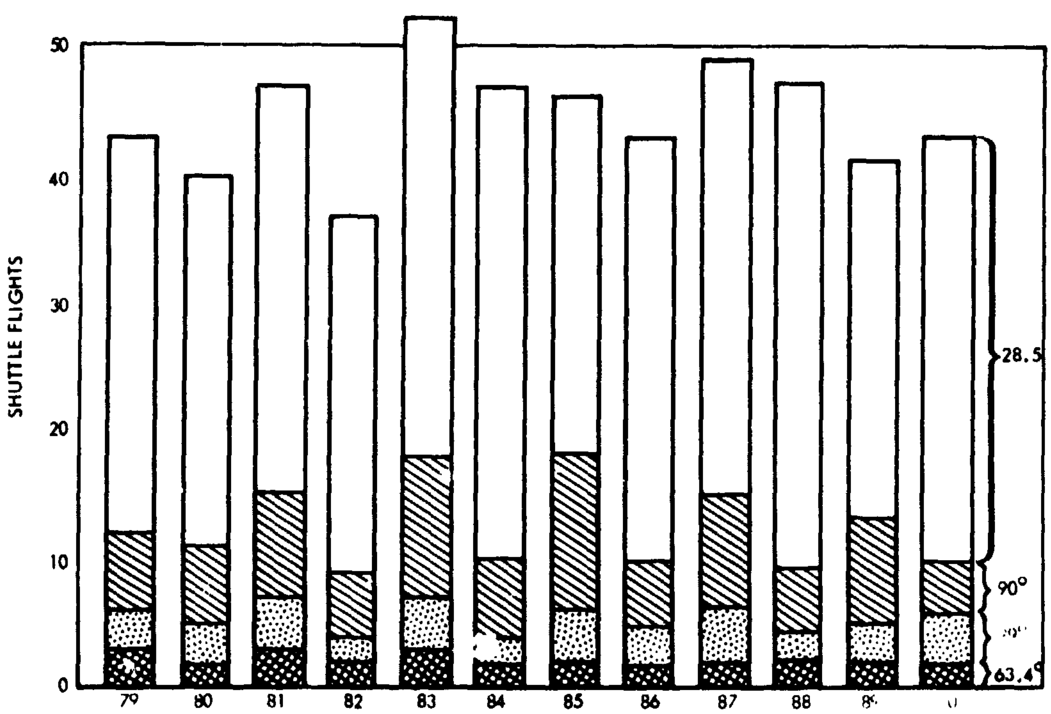


Figure 4-27 Space Shuttle Flights By Year (Case 1)

To define the Space Shuttle activity in terms other than just the number of flights in the individual inclination or launch site category, Figure 4-28 displays the activity in terms of flights required to supply propellant, payloads, and the Tug vehicles themselves. Of the 383 launches in the 28.5 to 30 degree inclinations approximately 60 percent take propellant with the remaining 40 percent being nearly equally split between Tug and spacecraft flights. For the higher inclined, lower activity orbit categories, however, this proportion changes so the majority of flights take up Tugs or spacecraft rather than propellants. For the 85 polar launches, the percentage of flights is 36, 46, and 18 for propellant, spacecraft, and Tugs, respectively. The other two categories have the 11 to 12 percent of the flights providing propellant, with the remainder nearly equally transporting payloads and Tugs.

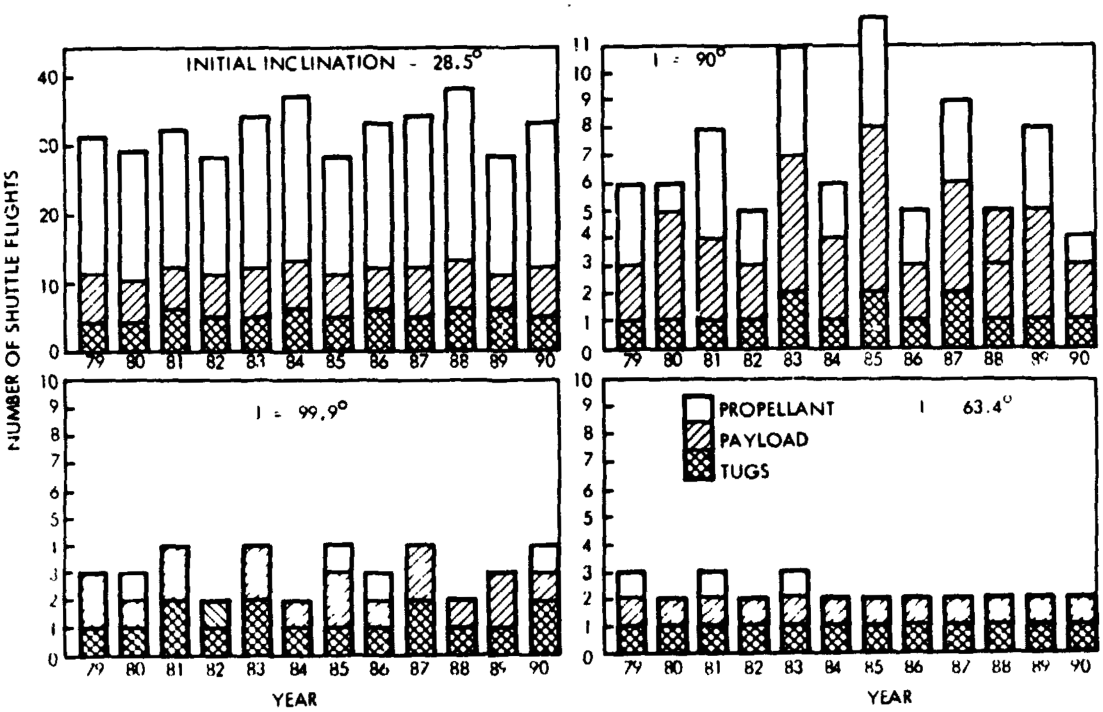


Figure 4-28 Breakdown of Shuttle Flight Requirements (Case 1)

Another exposition, in terms of activity level associated with space basing, is the number of Tug flights. Figure 4-29 displays, for the first case, the number of Tug flights in each of the four inclination angle categories for each of the years of the mission model. The numbers of orbital flights in the 28.5 to 30 degree category range from 31 in 1984 and 1988 to 22 in 1989. The activity in the polar and sun-synchronous classes is approximately equal, averaging about seven flights per year. One or two missions are flown on a yearly basis at 63.4 degrees. Comparing these numbers with the average Space Shuttle activity indicates approximately the same number of flights for both the Tug and Shuttle except in the 99 to 100 degree category where, on the average, more than twice as many Tug flights are made as are Shuttle flights. Referring to Figure 4-28 there are only four flights to orbit at the 99 to 100 degree inclination range required to provide Tug propellant; the remainder supply fully loaded Tugs or spacecraft. Because of the relatively low energy requirements for missions in this classification and the resulting operational characteristics as outlined above, a significant number of spacecraft missions are supported by one fully loaded Tug vehicle.

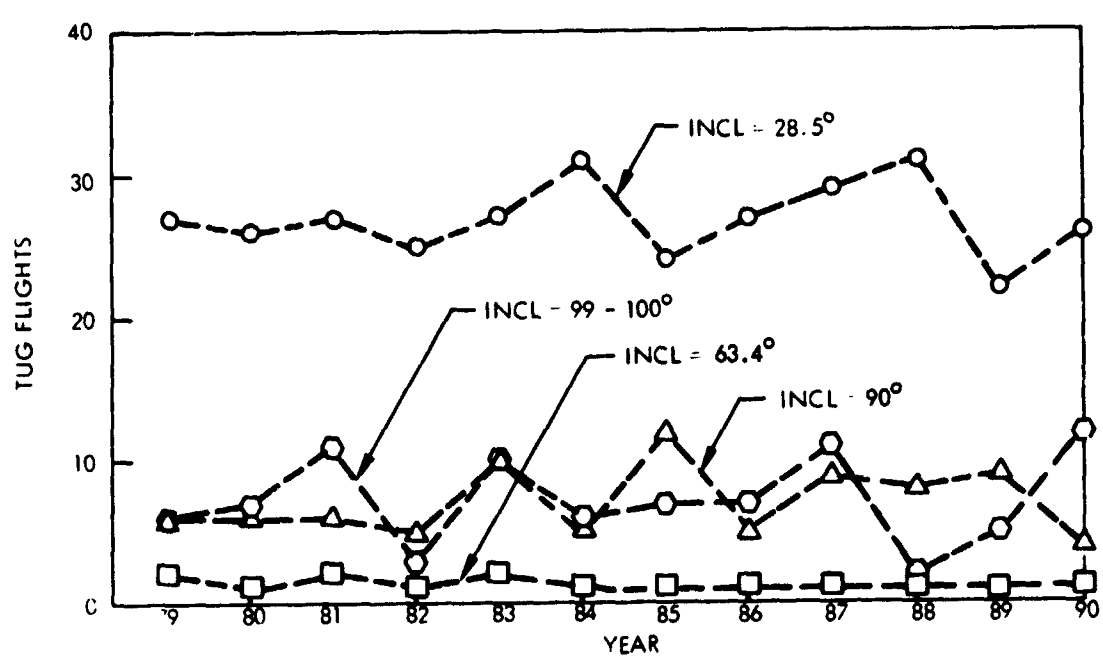


Figure 4-29 Annual Tug Flight Requirements by Inclination
(Case 1)

Paralleling the data display on the Shuttle activity, Figure 4-30 provides data relative to the composition of Tug flights at a particular inclination range. For Case 1 this figure provides, on a yearly basis, the number of flights that are either single-stage reusable, single-stage expendable or tandem-stage reusable for the 28.5 to 30 degree inclination angle category. In all, there are 156 single-stage-reusable, 157 tandem-stage-reusable and 9 single-stage-expendable flights. The 313 reusable flights equate to an average of 26 orbital launches per year, or more than 2 a month, together with less than one expendable flight on a yearly basis.

SPACE BASED CASE 1: INITIAL INCLINATION = 28.50

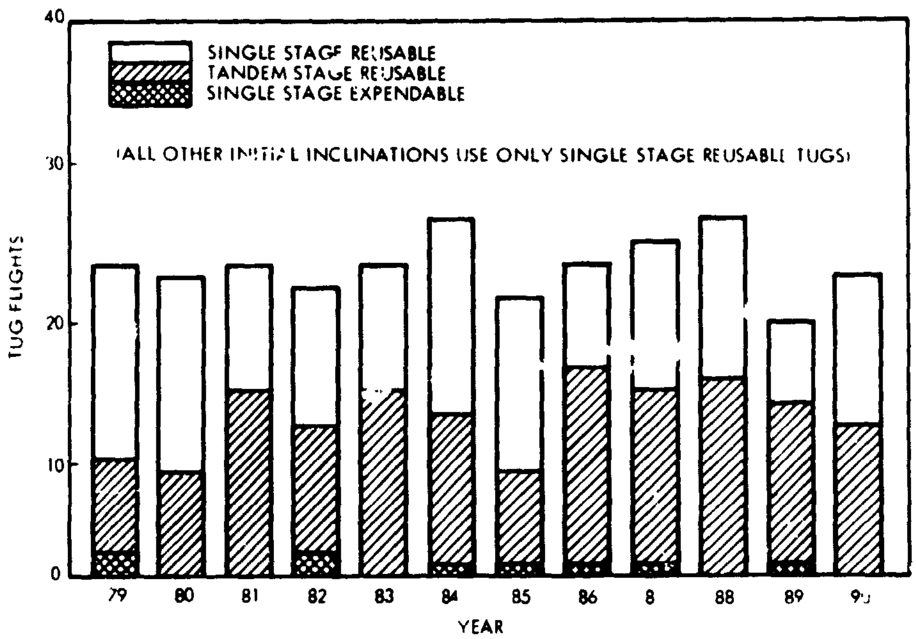


Figure 4-30 Tug Configuration Breakdown
(Case 1)

The same type of data presented for Case 1 in the previous four figures is now given for Case 2. Again, Case 2 is based upon the groundrule that the payloads and their associated orbital flight operations modes are identical to the ground-based minimum cost solution for the 50,200 lb reusable Tug. In order to have the same payloads and therefore the same payload costs, the Tug must have performance identical to that of the system used for the ground-based simulation. Figure 4-31 shows the number of Shuttle flights by year, by inclination angle, required to support the space-based transportation system for ground-based type payloads. Because there is not the predetermined emphasis of minimizing payload costs regardless of the impact on transportation as was assumed in Case 1, Case 2 shows a 10 percent reduction in the total number of Shuttle flights, accounting for some \$270 million undiscounted. The 482 flights in Case 2 are a reduction of 10 Shuttle flights a year for 12 years with respect to the 50,200 lb W_P ground-based system in which tandem stages were considered in all modes. The percentage distribution of the total flights in terms of the individual inclination angle categories is essentially identical to Case 1, with 69 percent at 28.5 to 30 degree inclination, 17 percent polar, and 7 percent polar, and 7 percent at both the 99 to 100 degree and 63.4 degree inclination angle groupings. The average number of flights at ETR is 28 per year with a maximum of 30 per year in 1984,

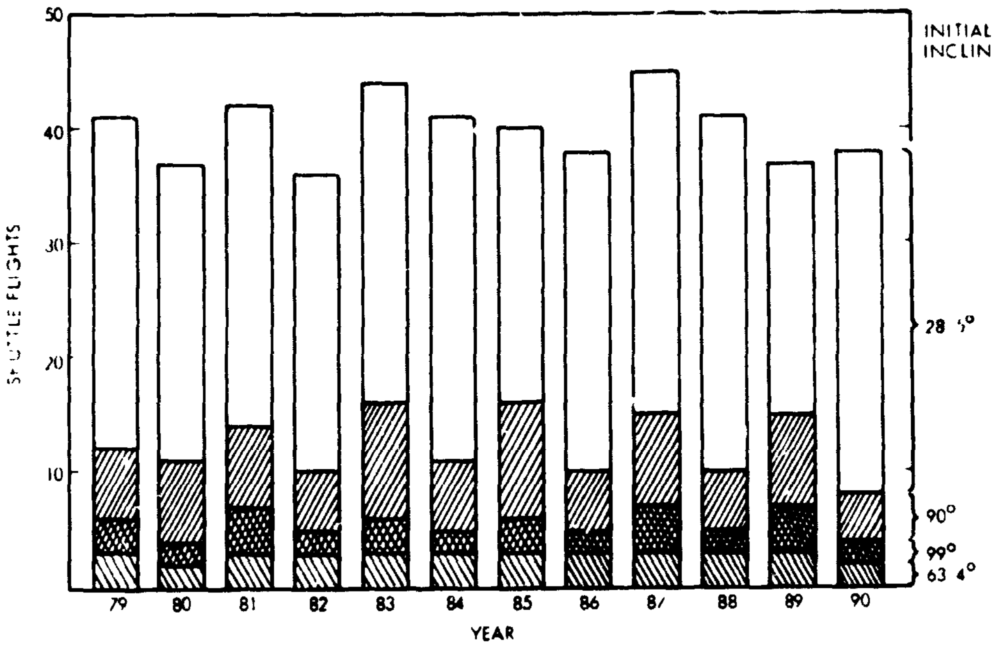


Figure 4-31 Space Shuttle Flights by Year
(Case 2)

1987, and 1990. The average of 28 represents a reduction of approximately four launches per year with respect to Case 1. The average activity for the other categories is approximately the same as Case 1, with Case 2 showing about one less launch per year for the highly inclined orbits as a group.

For Case 2 Figure 4-32 examines the distribution of Space Shuttle flights by inclination. The resulting distribution shows a pattern similar to Case 1. Even though the 28.5 to 30 degree orbit group accounts for more than 80 percent of the total reduction in the number of Shuttle flights between Cases 1 and 2, the percentage of flights transporting propellant, spacecraft, and Tugs is nearly identical to Case 1. Also as in Case 1, 70 percent or more of the Shuttle flights for the higher inclinations in Case 2 carry spacecraft and Tugs, rather than nearly 70 percent of the launches transporting propellant as is the case for missions with initial inclination angles of 28.5 to 30 degrees.

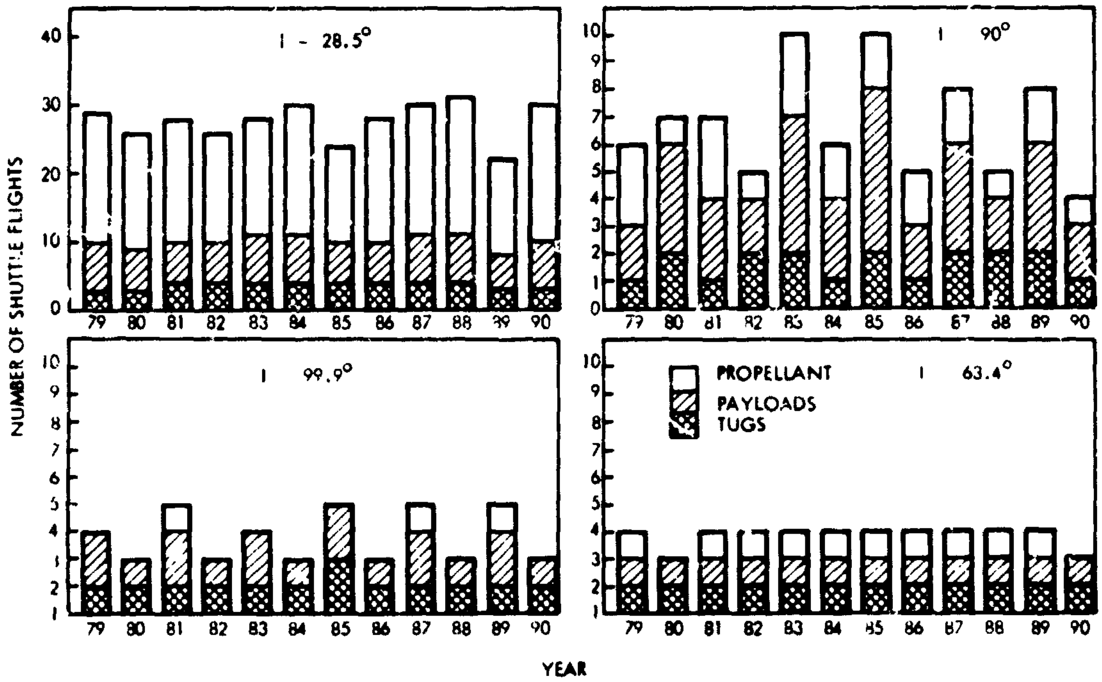


Figure 4-32 Breakdown of Shuttle Flight Requirements
(Case 2)

A breakdown of the Tug activity for the second space-basing case is presented in Figure 4-33. The number of orbital flights in the 28.5 to 30 degree inclination angle grouping ranges from a high of 29 in 1988 to a low of 20 in 1989, with an average of 26 per year. This compares with the nearly 27 flights per year in the same category for Case 1. The polar activity is somewhat greater at 9 flights per year in Case 2, compared to 7 per year in the first case; there is a decrease from 7 to 5 missions on a yearly basis for the sun synchronous orbit groupings. There are nearly 2 flights per year at the 63.4 degree inclination. With this redistribution of Tug and Shuttle activity, Case 2 shows that for both the 90 degree and 99 to 100 degree inclination angle categories there are from 20 to 30 Tug flights per year in excess of the number of Shuttle launches, indicating (as in Case 1) a large number of individual spacecraft being transported on one Space Tug propellant loading.

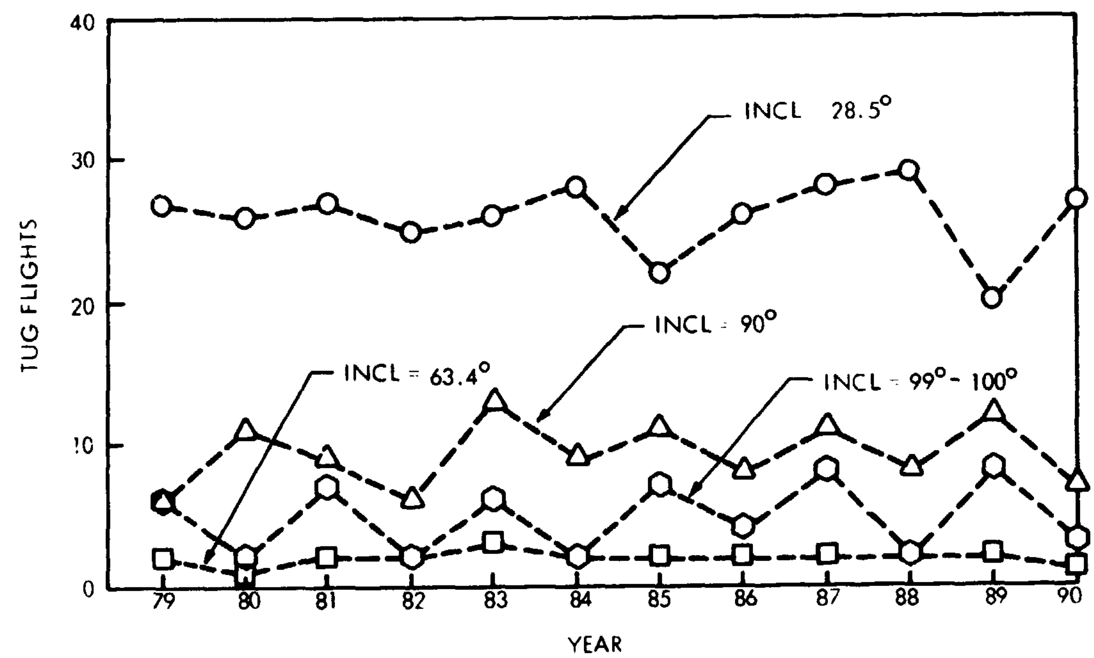


Figure 4-33 Annual Tug Flight Requirements by Inclination
(Case 2)

One of the most significant differences between Cases 1 and 2 is shown in Figure 4-34. This graph gives the breakdown of single-stage reusable and expendable as well as tandem-stage reusable flights for Case 2 in the 28.5 to 30 degree inclination category. While single-stage reusable Tug designs are used for the other three mission groupings, identical to Case 1 results, the 271 such flights out of ETR represent a 73 percent increase over the same flight category in Case 1. This increase in single-stage flights is caused by decreased use of tandem recoverable stages because of the desire to capture maximum payload effects. Half the difference between the number of tandem reusable flights in Case 1 and the number in Case 2 accounts for nearly all the decrease in the number of Space Shuttle flights. (A single Shuttle bay cannot accommodate tandem 50,200 lb W_P LO_2/LH_2 Tugs). There are the same 9 expendable flights, and in total there is the same average of two to three Tug flights per month of the 28.5 to 30 degree inclined orbits as occurred in Case 1.

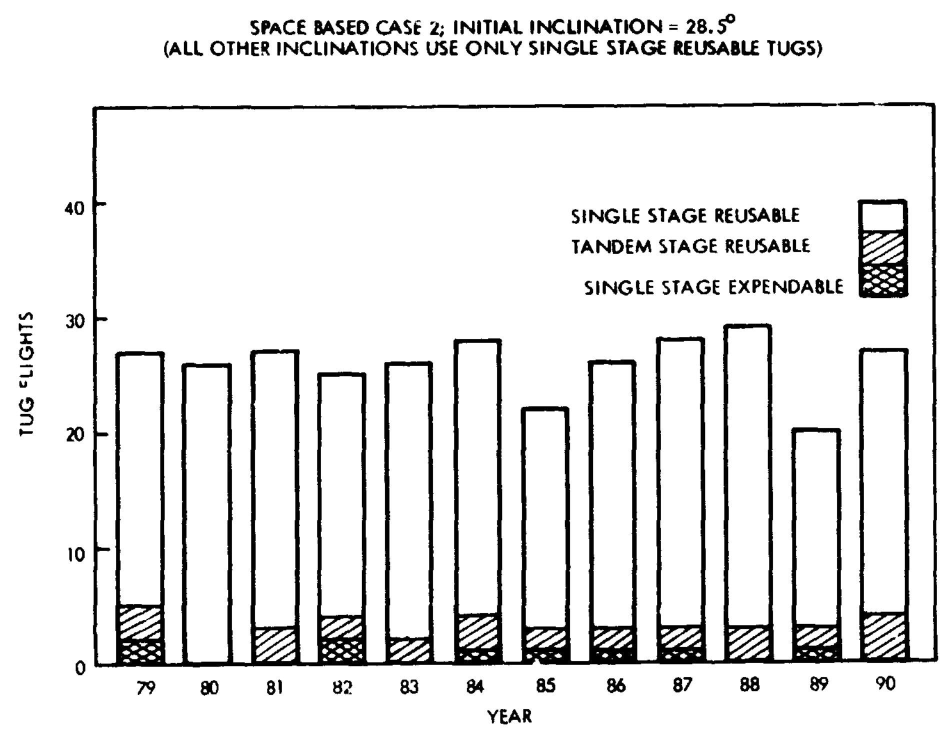


Figure 4-34 Tug Configuration Breakdown
(Case 2)

A tabular summary of the space-basing cases is presented in Table 4-14. This table provides an activity and cost breakdown by which to compare the data presented in the previous charts. The higher activity and fleet size requirements of Case 1 are offset in dollar terms by its relatively low payload costs. The \$15.562 billion payload costs in Case 2 are the same value as is associated with the 50,200 lb ground-based LO_2/LH_2 system. This shows that if the same performance could be achieved between ground- and space-based systems, over \$1.1 billion could be saved on transportation costs. Case 3 has both higher payload and transportation costs with respect to the other cases because of its decreased performance. Even so, the difference between Cases 1 and 3 is less than \$500 million undiscounted and less than \$120 million discounted at a 10 percent rate over the 12 year mission model.

Table 4-14 SPACE BASED VEHICLE REQUIREMENTS AND COST

LO_2/LH_2 – 50158 LB

CASE	FLEET SIZE			PROGRAM COSTS (UNDISCOUNTED) ($M)				TOTAL DISCOUNTED COST ($M)
	SPACE SHUTTLE FLIGHTS	SPACE TUG			TRANSPORTATION			
		VEHICLES	FLIGHTS*	PAYLOAD	TUG	SHUTTLE	TOTAL	
1	535	25	343/157/9	15218.67	1203.17	2675.00	19096.84	6405.36
2	482	20	465/28/9	15562.52	1103.31	2410.00	19075.83	6379.53
3	493	21	463/28/15	15751.76	1233.90	2465.00	19450.66	6517.50

*TUG FLIGHTS: (SINGLE STAGE REUSABLE/TANDEM STAGE REUSABLE/SINGLE STAGE EXPENDABLE)

As a final comparison Figure 4-35 relates the ground-based and space-based transportation systems. As indicated on the previous table, the difference between the best LO_2/LH_2 ground-based system and space-based Cases 1 or 2 is nearly $1.2 billion, undiscounted. Even Case 3, with its weight penalty for redundant and autonomous avionics, saves over $500 million. However, the operations of space-based Tugs are far less well defined than those of ground-based systems and consequently there is far greater uncertainty in the RDT&E and operations costs for space basing. Nontheless the potential savings of space-based Tugs will permit considerable growth in these cost elements before a crossover point with ground basing is reached.

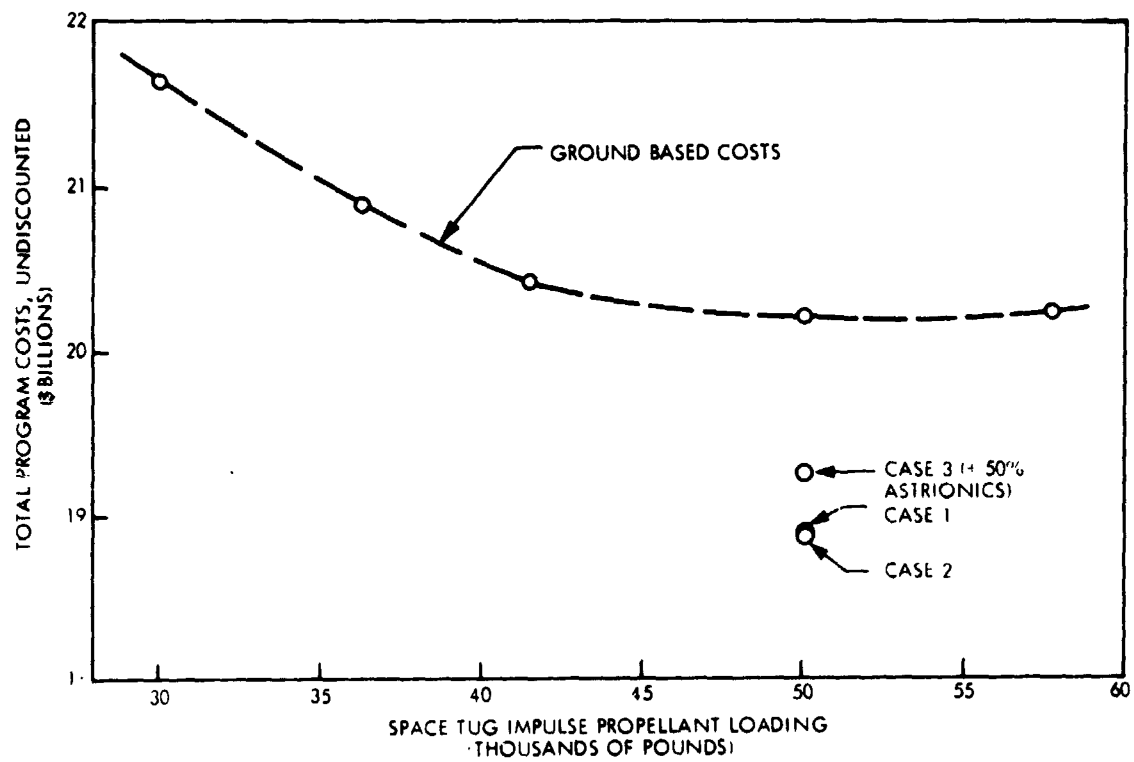


Figure 4-35 Ground Based/Space Based Tug Comparison

Tug Sensitivity Analyses

The second step in the data interpretation task was the series of sensitivity analyses conducted to define the effect of major system variables on total program cost. These sensitivity analyses covered two general categories of variables:

- External Factors. These are factors outside the influence of the Tug program. They include Shuttle user fee, Shuttle payload capacity (weight and size), and payload weights and costs.

- Tug Variables. These are factors directly influenced by the design or operating mode of the Tug. They include Tug mass fraction, specific impulse, lifetime, and refurbishment factors.

The first set of sensitivities answers the general question: What happens to these study results if some of the major programmatic variables change? The second set answers the question of a designer or program planner: What does the economic analysis mean in terms of specific implications to Tug system definition?

All of the data supporting these sensitivity studies were generated with STAR/ANNEX computer runs. Mathematica ran additional sensitivity studies using the TUGRUN program, and also quantified data from the Lockheed sensitivity analyses on the basis of allowable RDT&E costs; this effort is discussed in Part 2 of Volume II.

The sensitivity analyses performed by Lockheed are discussed in the following paragraphs.

Shuttle User Fee. A primary concern in evaluating the results of this study is the effect of increased Space Shuttle user fee. The study baseline value of $5 million per flight was based on a two-stage, fully-reusable Shuttle. In the time that this study has been in process the Shuttle has been redefined as a reusable orbiter with expendable tankage and a solid propellant first stage; the user fee is now estimated at $10.5 million per flight. To measure the impact of growth in the Shuttle user fee, STAR/ANNEX runs were made for two Tug concepts as the user fee was increased in two steps to $15 million per flight. The selected concepts were the Large Tank Agena OIS and the 50,200 lb LO_2/LH_2 reusable Space Tug. Results of this analysis are shown in Figure 4-36, which plots (in undiscounted dollars) the growth in transportation cost, payload cost, and total-program cost as Shuttle user fee increases from $5 million to $15 million.

The Large Tank Agena transportation and total program costs increase proportionately as the Space Shuttle user fee increases, because payload costs remain constant. In the case of the reusable Tug, however, the total payload cost is affected slightly by the Shuttle user fee because of the mode selection process. As the user fee increases, it becomes uneconomical for some programs to use the retrieval modes; thus, payload savings are lost, resulting in higher payload costs. Note, however, that a crossover in total program cost between the orbit injection stage and the reusable Tug does not occur in the range of Shuttle user fee investigated here; moreover, this conclusion seems valid to some point in user fee beyond $20 million per Shuttle flight.

Shuttle Payload-Carrying Capability. A second sensitivity dealing with the Space Shuttle is summarized in Figure 4-37. Because of some potential variations in Space Shuttle capacity, an analysis was undertaken in which the nominal Shuttle definition for this study was varied in two steps: (1) a reduction of 15 feet in cargo bay length (from 15 by 60 feet down to 15 by 45 feet), and (2) the above length reduction plus a reduction in the due-east 100 nm circular orbit payload-carrying capability of the Shuttle by 20,000 lb (from 65,000 lb down to 45,000 lb). This analysis was carried out for both the $5 million and $10 million Shuttle user fee values. Because of the anticipated effects of shortening the Shuttle cargo bay and reducing its load-carrying capability, a LO_2/LH_2 design smaller than the least-cost 50,200 lb system was chosen for this analysis. The Tug was assumed to have 36,200 lb of propellant.

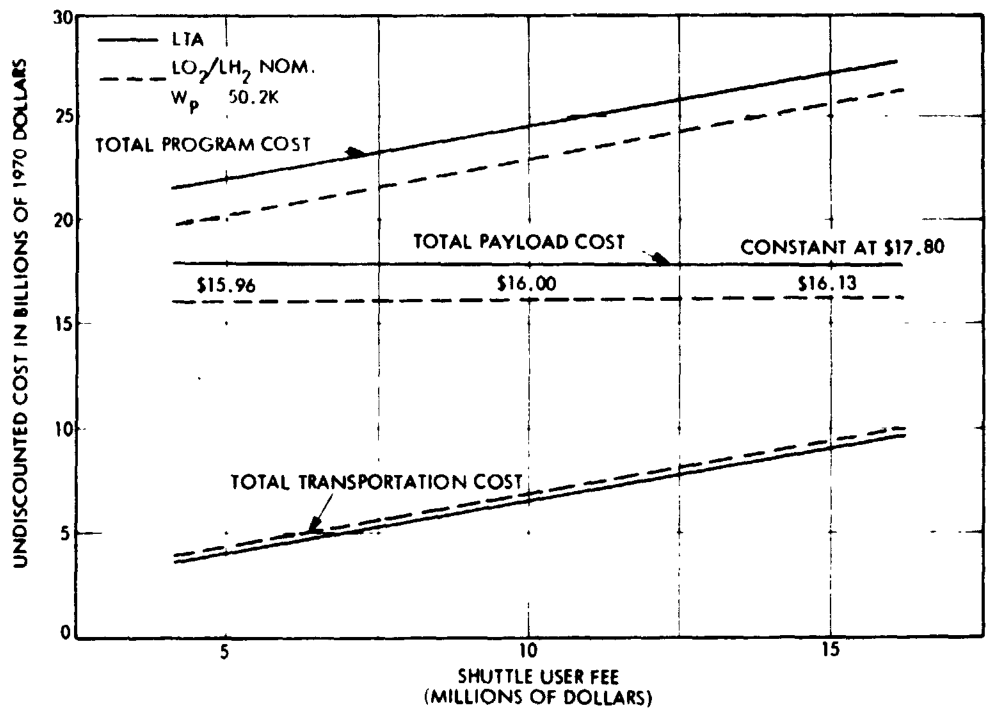


Figure 4-36 Cost Sensitivity to Shuttle User Fee

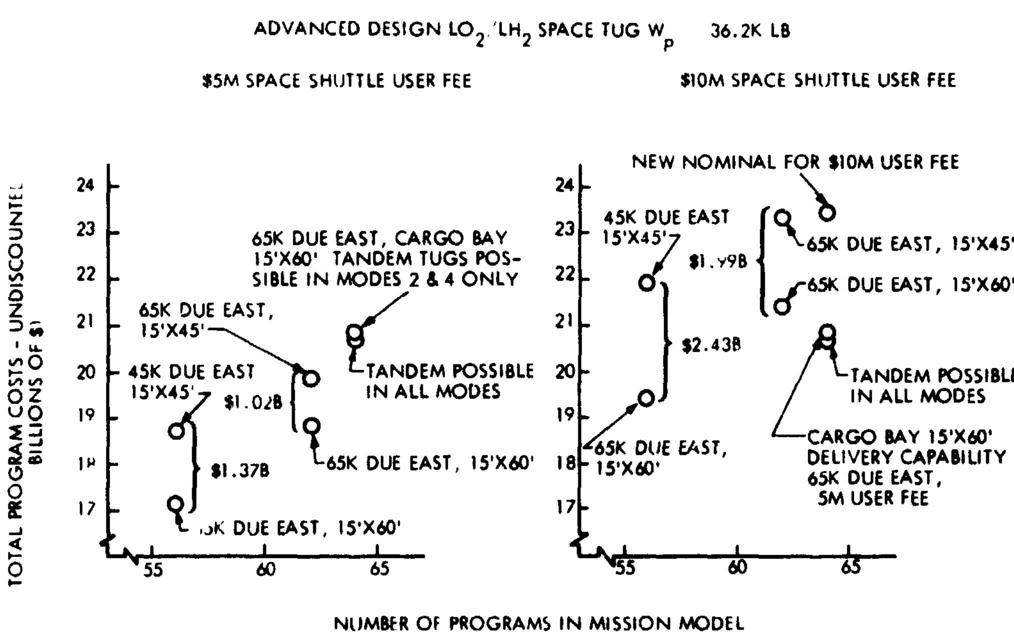


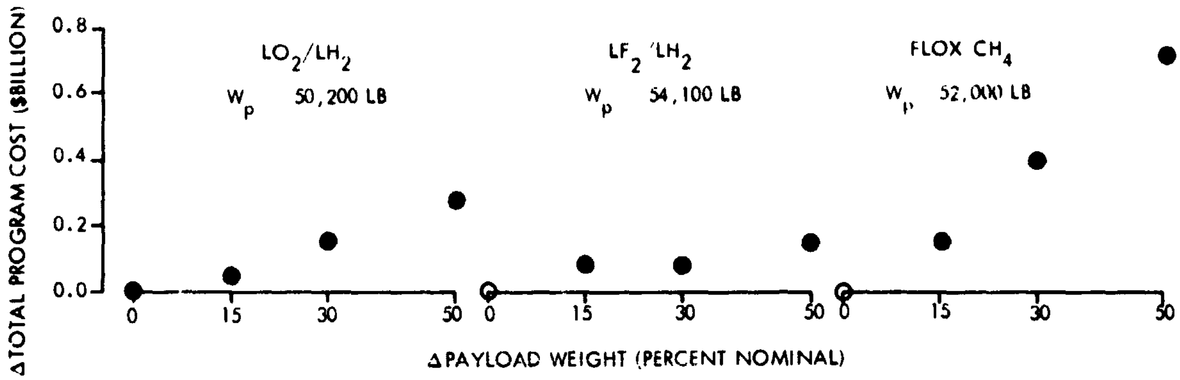
Figure 4-37 Cost Impact of the Variations in Space Shuttle Design

The first step in the Shuttle capacity perturbations (payload bay length reduction) had the effect of knocking out of the mission model two programs that had 60-foot-long spacecraft. The second step (45,000 lb due-east payload capability at 100 nm) knocked out an additional 6 missions, all in the highly inclined orbit categories, because the Shuttle was unable to take either the payload or the Tug and its required propellants to orbit. The bottom data points on both graphs, labelled 65,000 lb due-east, 15 by 60 ft, represent the nominal points with the full 65 programs as reduced in cost by the deletion of the missions just mentioned. Evaluating these cases in terms of the Shuttle perturbations on the remaining missions produces the \$1.02 to \$1.37 billion increase in total program cost at a \$5 million user fee, and a corresponding \$1.99 to \$2.43 billion increase for a \$10 million Shuttle fee. These delta costs specifically exclude the economic impact of the inability to perform the 2 or 8 missions which fall out of the model, and thus reflect only the decrease in payload effects captured and the increased average transportation costs.

Unmanned Payload Influences. The final set of sensitivities run for variables external to the Tug program concerned the influences of unmanned payload weights and costs on the Tug system economics.

The effect of payload weight growth on total program cost was evaluated for three reusable Tug configurations. In the measurement of this sensitivity, all baseline payload weights for each program were increased by 15, 30 and 50 percent, resulting in three off-nominal mission models. For each perturbed mission model and each candidate Space Tug, the undiscounted total program cost was evaluated. The resulting increases in total program cost as a function of the percentage payload growth are presented in Figure 4-38 as discrete points for each Tug configuration. A breakdown of the total program cost into the payload, Space Shuttle, and Tug costs is also presented in tabular form.

Comparison of the tabular data reveals that for the LO_2/LH_2 and LF_2/LH_2 stages the Tug-related costs represent less than 13 percent of the increase in total program cost, whereas, for the $FLOX/CH_4$ stage the Tug costs make up as much as 28 percent. For all configurations the dominant cost component for the change in total program



PROGRAM COSTS ($MILLIONS)

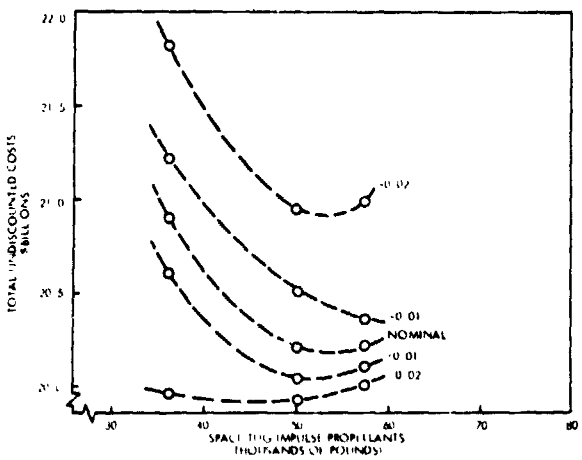
% ΔPL / COSTS	LO_2/LH_2 0	15	30	50	LF_2/LH_2 0	15	30	50	$FLOX/CH_4$ 0	15	30	50
PAYLOAD	15,563	15,647	15,669	15,654	15,274	15,284	15,284	15,372	15,658	15,687	15,723	15,949
SHUTTLE	3,005	2,975	3,050	3,155	2,880	2,940	2,940	2,915	2 785	2,865	3,030	3,070
TUG	1,410	1,406	1,415	1,447	1,535	1,546	1,546	1,542	1,334	1,376	1,421	1,481
TOTAL PROG	19,978	20,028	20,134	20,256	19,689	19,770	19,770	19,829	19,777	19,928	20,174	20,500

Figure 4-38 Sensitivity to Payload Weight Growth

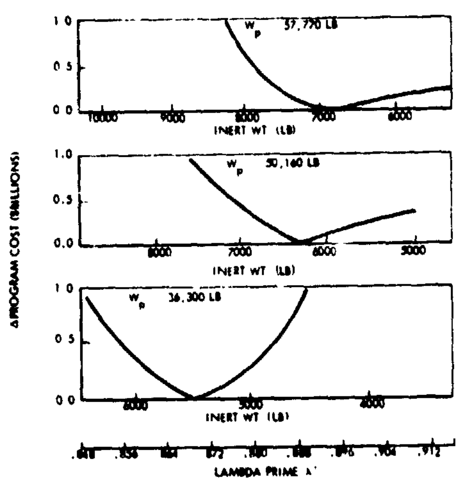
cost is the Space Shuttle user fee. This indicates that payload growth will significantly increase the Space Shuttle activity and, hence, the sensitivity of total program cost to increases in Shuttle user fee. These results indicate that the LF_2/LH_2 Tug is least sensitive to across-the-board increases in payload and that the reference $FLOX/CH_4$ Tug (divided tank design) is the most sensitive.

Tug Mass Fraction. The first of the sensitivity analyses conducted for Tug program variables was stage mass fraction (λ'). The variation in total program cost for changes of ±0.01 and ±0.02 from the baseline Tug mass fraction values was assessed for three propellant combinations, namely LO_2/LH_2, LF_2/LH_2, and $FLOX/CH_4$.

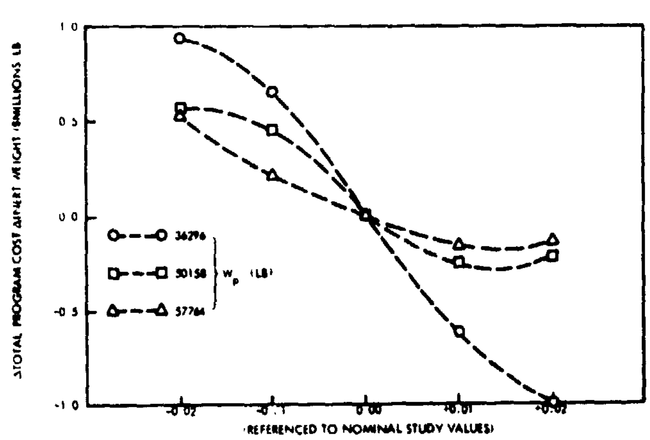
For the LO_2/LH_2 Tug, λ' variations were evaluated for Tugs with propellant weights of 36,300, 50,200 and 56,700 lb; the corresponding nominal mass fractions were 0.852, 0.873, and 0.880, respectively. Results of this analysis are presented in Figure 4-39 and Table 4-15. In Figure 4-39 the first set of curves presents the variation in total program cost as a function of impulse propellant and delta lambda prime. The second set of curves presents the absolute value of delta total program



Total Program Cost vs Propellant Loading



ΔProgram Cost vs Inert Weight and λ'



Rate of Change in Total Program Cost

Figure 4-39 Mass Fraction Sensitivities For LO_2/LH_2 Tugs

Table 4-15. TABULAR DATA FOR LO_2/LH_2 TUG LAMBDA PRIME SENSITIVITY ANALYSIS

Propellant Weight		Total Undiscounted Cost ($ Millions)				Δ Cost ($ Millions)				% Payload Effects Captured
	$\Delta\lambda'$	Tug	Shuttle	Payload	Total Program	Tug	Shuttle	Payload	Total Program	
	-.02	2591	2600	16,638	21,829	941	45	-60	926	70.1
	-.01	1949	2590	16,685	21,224	299	35	-13	321	69.1
36,300	Nominal	1650	2555	16,698	20,903	-	--	-	-	69.0
	+.01	1532	2830	16,250	20,612	-118	275	-448	-291	78.3
	+.02	1317	2560	16,093	19,970	-333	5	-605	-933	81.7
	-.02	1659	2835	16,461	20,954	222	25	498	744	73.8
	-.01	1503	2840	16,159	20,502	66	30	196	292	80.3
50,200	Nominal	1437	2810	15,963	20,210	-	--	-	-	84.7
	+.01	1355	2790	15,904	20,049	-82	-20	-59	-161	85.9
	+.02	1361	2835	15,738	19,934	-76	25	-225	-276	89.3
	-.02	1634	3135	16,228	20,997	181	250	348	779	78.8
	-.01	1456	2955	15,958	20,369	3	70	78	151	84.6
57,800	Nominal	1453	2885	15,880	20,218	-	--	-	-	86.4
	+.01	1378	3005	15,723	20,106	-75	120	-157	-112	89.6
	+.02	1365	2955	15,705	20,024	-88	70	-175	-194	90.0

cost as a function of λ'. Along the λ' scale in this figure, the corresponding stage wet inert weight is pegged to help identify the weight increments associated with ±0.01 and ±0.02 changes in λ'. This scale is nonlinear because of the nonlinear relationship between λ', propellant weight, and inert weight. The third set of curves plots the change in total program cost with respect to the absolute value of a variation in stage inert weight. From these curves the following observations can be made:

1. The smaller Tugs (36,000 lb) exhibit roughly comparable sensitivity for increases or decreases of λ', whereas the heavier Tugs show a greater sensitivity to decreases in λ' than to increases.
2. The measure of undiscounted cost savings for improving the λ' of the less efficient Tug is about one million dollars per pound (with respect to the nominal), and for the more efficient Tugs is several hundred thousand dollars per pound.
3. The positive increases in λ' result in a dimishing return for the larger Tug sizes. This suggests that the larger stages are operating within an efficient (insensitive) region.

In Table 4-15 the variations in Tug, Space Shuttle, and payload costs are tabulated for each propellant weight and λ' variation, along with the relative effect of each cost component on the variation in total program cost. The following observations can be made from this data:

1. For a 36,300 lb propellant weight
   - Inert weight increases cause Tug costs to be the major contribution to increases in total program cost
   - For inert weight decreases, the combination of Tug and payload costs are the main contributors to the decrease of total program cost
2. For the 50,200 lb propellant weight
   - For both inert weight increases and decreases the payload and Tug costs are the main contributors to the total program cost variations
3. For the 56,700 lb propellant weight
   - Increases in inert weight cause increases in Tug costs, Space Shuttle user costs, and payload costs
   - Decreases in inert weight result in decreased Tug and payload costs but increased Space Shuttle transportation costs.

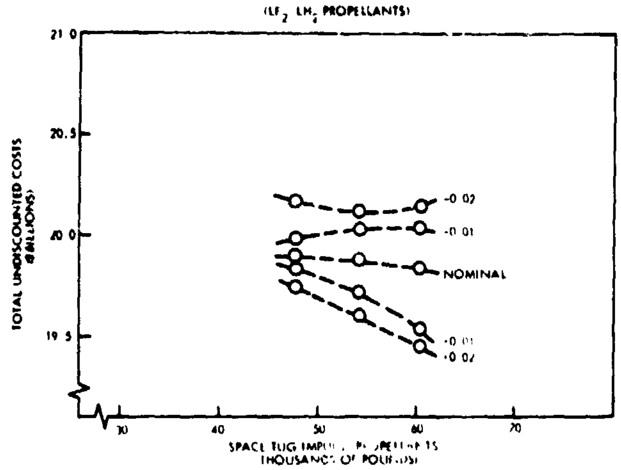
The inconsistency of each of these cost components across the propellant range is a result of choosing the optimum mode based on minimum program cost, and upon the discrete factors (such as Tug length, Tug offloading, etc.) that affect the Tug and Shuttle flight requirements and the attainable payload benefits.

For the LF_2/LH_2 Tug, λ' variations were evaluated for Tugs with propellant loadings of 47,800 lb, 54,100 lb, and 60,600 lb; the corresponding baseline mass fractions were 0.882, 0.889, and 0.895, respectively. Results for the LF_2/LH_2 sensitivities are presented in Figure 4-40 and Table 4-16 in the same format as for the LO_2/LH_2 λ' sensitivities.

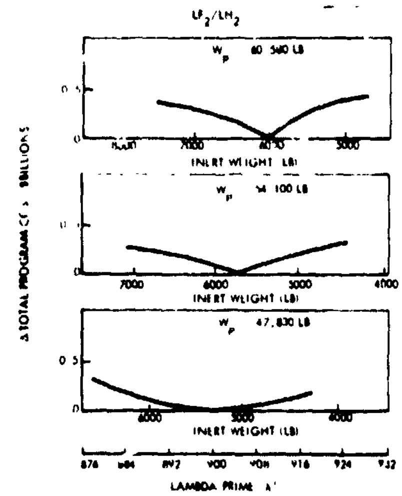
Because of the higher structural efficiency of these Tugs (compared to LO_2/LH_2 configuration) and the higher I_{sp} of the LF_2/LH_2 propellant combination, the flourine-hydrogen Tugs are generally less sensitive in total program cost to λ' than the LO_2/LH_2 Tugs. Note, however, that larger LF_2/LH_2 Tugs are more sensitive to moderate (±0.01) shifts in λ' than is the 47,800 lb size.

Examination of the tabular data presented in Table 4-16 indicates that across the propellant weight range the payload costs are the main contributors to the total program cost variations. The relative insensitivity of the transportation costs for the LF_2/LH_2 Tug indicates that the selection of the size of the LF_2/LH_2 Tug should be based on criteria other than the total-program-cost rankings of this class of Tug.

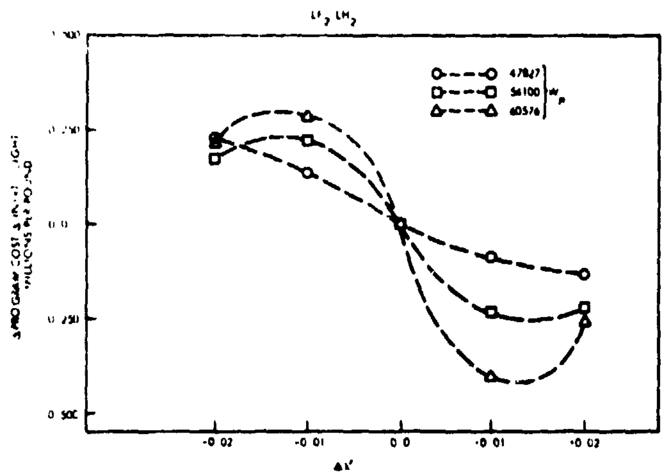
For the FLOX/CH_4 Tug, λ' variations were evaluated for Tugs with propellant loadings of 44,000 lb, 52,000 lb, and 58,900 lb. The corresponding baseline mass fractions were 0.888, 0.897, and 0.904, respectively. Results for the FLOX/CH_4 sensitivities are presented in Figure 4-41 and Table 4-17 in the same format as for the other two propellants. Though the FLOX/CH_4 Tug has a higher structural efficiency than LO_2/LH_2 Tugs, its lower specific impulse (414 sec vs 460 sec) causes these Tugs to be as sensitive to λ' variations as the LO_2/LH_2 stage. These sensitivities have characteristics similar to those of the LO_2/LH_2 Tugs. For the lower propellant weights, near-symmetrical cost savings and penalties result. However, for the larger propellant weights diminishing cost savings result for improvements in λ', whereas severe cost penalties result for decreases in λ'.



Total Program Cost vs Propellant Loading



Δ Program Cost vs Inert Weight and λ'

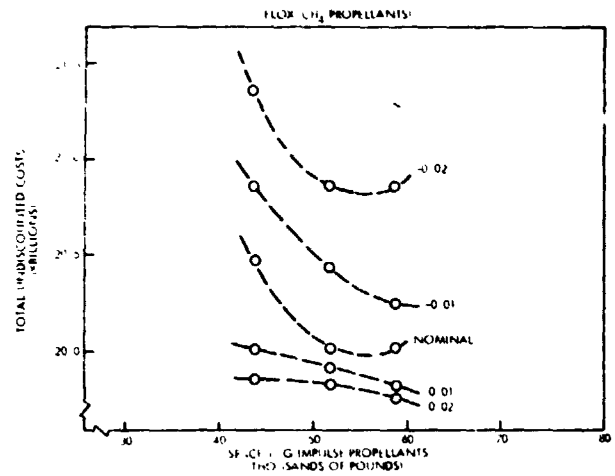


Rate of Change in Total Program Cost

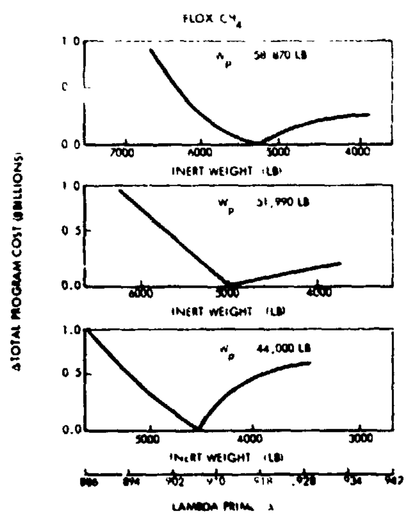
Figure 4-40 Mass Fraction Sensitivities For LF_2/LH_2 Tugs

Table 4-16. TABULAR DATA FOR LF_2/LH_2 TUG LAMBDA PRIME SENSITIVITY ANALYSIS

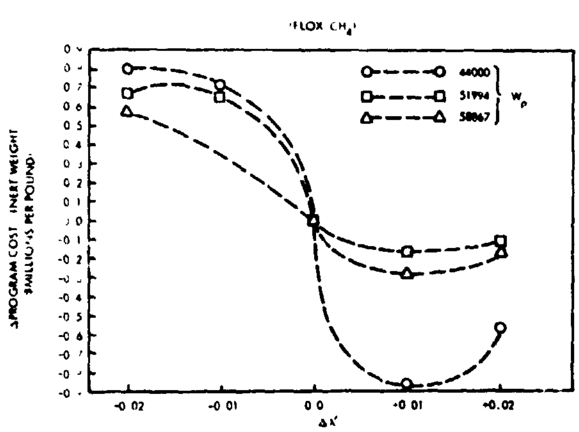
Propellant Weight	Total Undiscounted Cost ($ Millions)					Δ Cost ($ Millions)				% Payload Effects Captured
	Δλ'	Tug	Shuttle	Payload	Total Program	Tug	Shuttle	Payload	Total Program	
47,800	-.02	1532	2675	15,975	20,182	69	6	203	272	84.4
	-.01	1453	2615	15,925	19,993	-10	-60	153	83	85.5
	Nominal	1463	2675	15,772	19,910	-	-	-	-	88.8
	+.01	1474	2700	15,685	19,859	11	25	-87	-51	90.6
	+.02	1453	2680	15,618	19,751	-10	5	-154	-159	92.1
54,100	-.02	1558	2655	15,909	20,122	67	-95	260	232	85.8
	-.01	1484	2775	15,780	20,039	-7	25	131	149	86.5
	Nominal	1491	2750	15,649	19,890	-	-	-	-	91.6
	+.01	1495	2745	15,495	19,735	4	-5	-154	-155	94.7
	+.02	1461	2650	15,490	19,601	-30	-100	-159	-289	94.8
60,600	-.02	1589	2665	15,906	20,160	80	-120	360	319	85.9
	-.01	1588	2750	15,712	20,050	79	-35	166	209	90.1
	Nominal	1509	2785	15,546	19,841	-	-	-	-	93.6
	+.01	1506	2750	15,291	19,547	-3	-35	-255	-294	99.1
	+.02	1499	2695	15,275	19,469	-10	-90	-271	-372	99.4



Total Program Cost vs Propellant Loading



Δ Program Cost vs Inert Weight and λ'



Rate of Change in Total Program Cost

Figure 4-41 Mass Fraction Sensitivities For FLOX/CH_4 Tugs

Examination of the tabular data presented in Table 4-17 indicates that for decreases in λ' the magnitude of the variation in total program costs is relatively insensitive to the Tug propellant weight (i.e., uniformly high). The Tug and payload costs are the main contributors to this variation. For increases in λ' all three cost components contribute cost savings for the small Tug, whereas for the 52,000 lb and 58,900 lb sizes the main cost savings result from reduction in Tug and payload costs.

Tug Engine Specific Impulse. The next Tug cost sensitivity investigated was specific impulse of the main engine. This analysis, conducted for the baseline LO_2/LH_2 propellant combination only, explored a range of I_{sp} values from 470 sec for the upper bound to 444 sec for the lower capacity (compared to the 460 sec nominal value). For purposes of analysis only, the RL10 engine was used to represent the 444 sec case. Important assumptions made for this engine were as follows:

- The RL10 engine would be developed sufficiently to permit idle mode start, so that the stage pressurization system weights would not increase over the baseline Tug values
- The RL10 would be extended in lifetime to whatever level is needed for reusable Tug service.

A reduced development cost, covering the estimated value of these RL10 upratings, was used in place of the 460 sec engine development cost. An increased RDT&E cost was used for the 470 sec engine development.

The I_{sp} sensitivity study results (Figure 4-42 and Table 4-18) showed surprisingly small differences in total program cost over the range of propellant weights for 36,300 lb to 57,800 lb. The magnitude of the differences, in undiscounted dollars, ranged from about ±70 million dollars at 50,200 lb to ± $190 millions at 36,300 lb.

The partial derivative of total program cost with respect to specific impulse (presented in the second set of curves in Figure 4-42) represents the slope of the total program cost curve when plotted as a function of I_{sp} for contours of constant propellant weight. Of the three LO_2/LH_2 Tugs considered, the 50,200 lb Tug is the least sensitive to variations in specific impulse. The 56,700 lb Tug showed a larger sensitivity than the 50,200 lb Tug for the 444 sec case because of the necessity to offload propellant for large stages to meet the Space Shuttle load-carrying constraint.

Table 4-17. TABULAR DATA FOR FLOX/CH_4 TUG LAMBDA PRIME SENSITIVITY ANALYSIS

Propellant Weight	Total Cost ($ Millions, Undiscounted)					Δ Cost ($ Millions)				% Payload Effects Captured
	Δλ'	Tug	Shuttle	Payload	Total Program	Tug	Shuttle	Payload	Total Program	
44,000	-.02	2122	2580	16,657	21,359	696	-120	233	799	69.9
	-.01	1583	2585	16,694	20,862	157	-115	270	302	69.0
	Nominal	1426	2700	16,424	20,560	-	-	-	-	74.8
	+.01	1298	2590	16,123	20,011	-128	-110	-301	-549	81.3
	+.02	1266	2570	16,033	19,869	-160	-130	-391	-691	83.2
52,000	-.02	1633	2705	16,530	20,868	307	95	450	852	72.6
	-.01	1487	2730	16,214	20,431	161	120	134	415	79.3
	Nominal	1326	2610	16,080	20,016	-	-	-	-	32.2
	+.01	1313	2590	16,008	19,911	-13	-20	-72	-105	83.7
	+.02	1295	2680	15,846	19,821	-31	70	-234	-195	87.2
58,900	-.02	1641	2715	16,499	20,855	267	40	535	842	73.2
	-.01	1455	2705	16,092	20,252	81	30	128	239	81.9
	Nominal	1374	2675	15,964	20,013	-	-	-	-	84.7
	+.01	1320	2715	15,774	19,809	-54	40	-190	-204	88.7
	+.02	1326	2710	15,719	19,755	-48	35	-245	-258	89.9

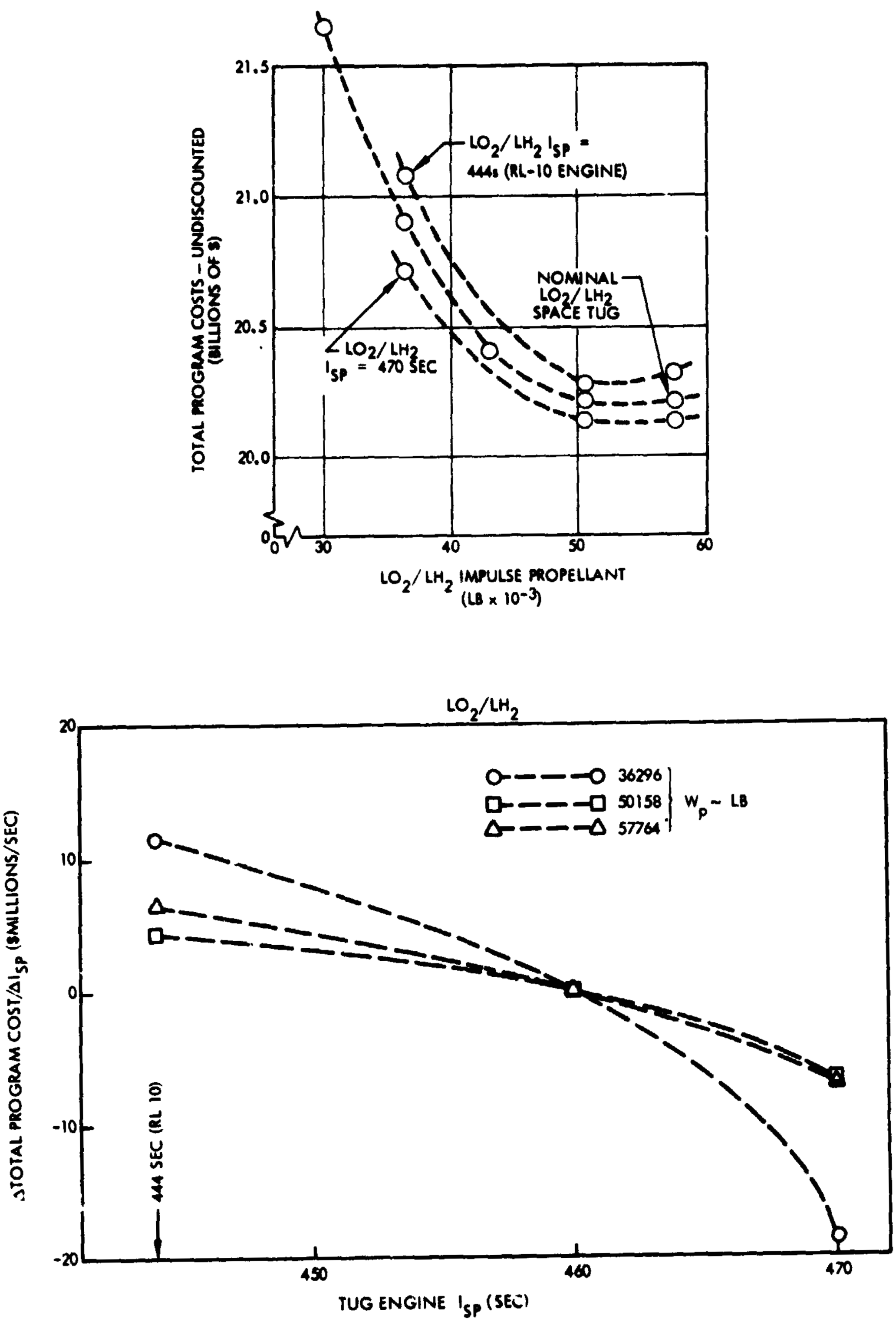


Figure 4-42 I_{sp} Sensitivity For LO_2/LH_2 Tugs

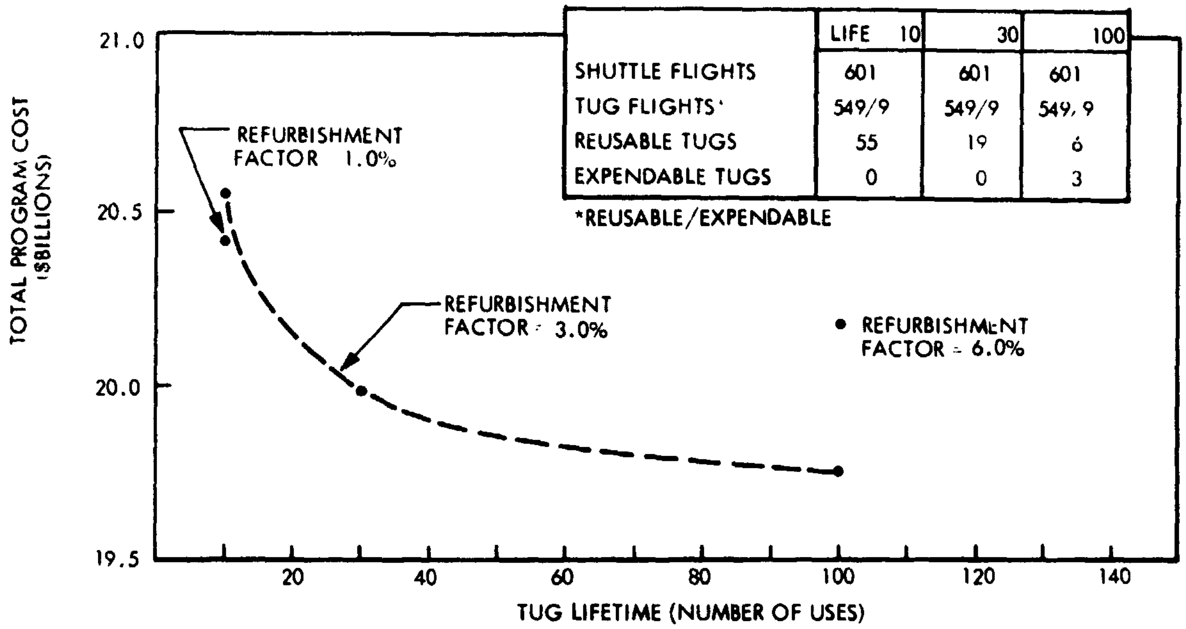
Table 4-18. TABULAR DATA FOR LO_2/LH_2 TUG SPECIFIC IMPULSE SENSITIVITY ANALYSIS

Propellant Weight	Total Cost ($ Millions Undiscounted)					Partial Derivative of Cost With Respect to I_{SP}				% Payload Effects Captured
	I_{SP}	Tug	Shuttle	Payload	Total Program	Tug	Shuttle	Payload	Total Program	
36,300	444	1819	2590	16,679	21,088	169	35	-20	184	69.4
	460	1650	2555	16,699	20,904	-	-	-	-	69.0
	470	1563	2680	16,473	20,716	-87	125	-226	-188	74.5
50,200	444	1386	2785	16,110	20,281	-51	-25	147	71	81.6
	460	1437	2810	15,963	20,210	-	-	-		84.7
	470	1375	2850	15,916	20,141	-62	40	-47	-69	85.7
57,800	444	1385	2985	15,953	20,323	-68	100	73	105	84.9
	460	1453	2885	15,880	20,218	-	-	-		86.4
	470	1482	2945	15,721	20,148	29	60	-159	-70	89.9

The tabular data in Table 4-18 indicates that for the 36,300 lb Tug the decrease in I_{sp} results in a large Tug cost increase with relatively small Space Shuttle and payload cost changes. For an I_{sp} increase, Tug and payload costs decrease while Space Shuttle costs increase; however, a net savings of $190 million results. For the 50,200 lb Tug the decrease in I_{sp} causes an increase in payload costs that dominates the total program cost variation; for this same Tug the increase in I_{sp} results in Tug and payload cost savings and a Space Shuttle cost increase, with the net result a $69 million savings. For the 56,700 lb Tug the decrease in I_{sp} causes a Tug savings and Space Shuttle and payload cost increases resulting in a total program cost increase of $105 million; for this same Tug an increase in I_{sp} results in spending $89 million in transportation costs to save $159 million in payload costs, for a net savings of $70 million.

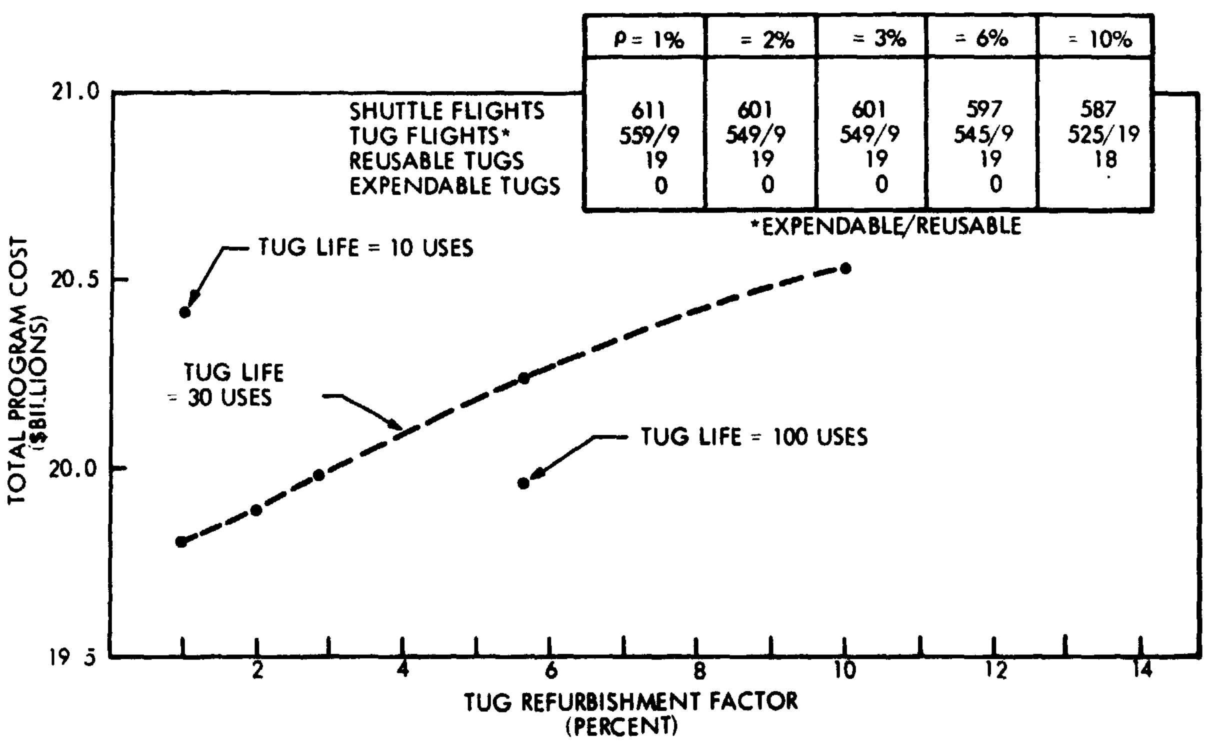
Tug Lifetime and Refurbishment Cost. The final sensitivity study conducted by Lockheed considered the impact of Tug lifetime and refurbishment costs on the total Tug program cost. This analysis was aimed at defining the benefits and costs parametrically, and not at establishing expected values for Tug life or refurbishment cost. The approach used in conducting this lifetime/refurbishment study was to calculate with STAR/ANNEX the total program costs for varying values of Tug lifetime, refurbishment cost, and first-unit cost. The results of this analysis are presented in Figure 4-43.

The upper graph plots undiscounted total program cost as a function of Tug lifetime for the 50,200 lb ground-based LO_2/LH_2 configuration. This curve shows dimishing economic returns as lifetime is increased from 10 to 100 uses (holding refurbishment factor constant at the baseline value of three percent). The rapid decline in cost between 10 and 30 uses occurs primarily because a smaller fleet of reusable Tugs can be purchased as the lifetime of each Tug increases. Dimishing returns occur when the number of Tugs to be amortized reaches the minimum fleet size. In fact, Tug lifetimes of 100 uses require that expendable vehicles be purchased to perform the escape missions that would ordinarily be assigned to Tugs approaching their design lifetime.



	LIFE 10	30	100
SHUTTLE FLIGHTS	601	601	601
TUG FLIGHTS*	549/9	549/9	549/9
REUSABLE TUGS	55	19	6
EXPENDABLE TUGS	0	0	3

*REUSABLE/EXPENDABLE



	ρ = 1%	= 2%	= 3%	= 6%	= 10%
SHUTTLE FLIGHTS	611	601	601	597	587
TUG FLIGHTS*	559/9	549/9	549/9	545/9	525/19
REUSABLE TUGS	19	19	19	19	18
EXPENDABLE TUGS	0	0	0	0	.

*EXPENDABLE/REUSABLE

Figure 4-43 Cost Sensitivity to Tug Lifetime and Refurbishment Factor

The lower graph plots total program cost as a function of Tug refurbishment factor, holding lifetime constant at the baseline value of 30 uses. Refurbishment factor, ρ, is defined as the ratio of average refurbishment cost-per-flight to the cost of a new unit. The range of values explored for ρ was from one to ten percent, a range that encompasses the expected high and low variations in refurbishment factor based on historical analogies. For reference, the historically derived value of ρ for an analogous vehicle, the X-15, was estimated as 2.3 percent over 32 flights in calendar year 1965. This suggests that the value derived in the study cost methodology (three percent) is reasonable. The results of this analysis show that, over the given range of ρ, the curve of total program cost is linear, indicating that the economic gain from reduced refurbishment costs is steady and free from diminishing returns.

Note that, in the range of Tug lifetimes and refurbishment factors analyzed here, the total program cost for the 50,200 lb LO_2/LH_2 reusable Tug never rises to the level of the least costly orbit injection stage.

Tug Funding

To complete the Lockheed data integration and interpretation effort, an analysis was made of Tug funding requirements.

The funding requirements for a typical orbit injection stage and a typical reusable Tug are compared in Figure 4-44. These expenditures include Tug/OIS funding for RDT&E, fleet investment, and 12 years of operation; they specifically exclude payload costs and Shuttle user fees. The Tug RDT&E cost was spread over five years. The funding curves represent gross requirements by year; no smoothing was performed.

The purpose of this analysis was to establish the trends of early-year peak funding, operational-program support levels, and total Tug expenditures. The graph at the left presents expenditure requirements by fiscal year of the Large Tank Agena. Its funding curve reflects a typically low RDT&E expenditure, expecially in the FY 1976-77 period when the Shuttle will be in final development, but peaks in the FY 1979-90 operational period. By contrast, the reusable Space Tug (right hand graph) has high funding requirements in the early time period ($193 million RDT&E in FY 1976) but these requirements drop during the operational phase because of system operating efficiencies. Overall, the reusable Tug requires less total investment than the orbit injection stages.

No acceptable early-year funding limits for the Tug program were specified by NASA; however, the following general observations are valid with respect to Tug funding in the time period through FY 1978:

- To keep early Tug funding under $50 million in the peak year, the Tug concept used in the initial operational capability (IOC) period of the Space Transportation System must be an orbit injection stage; this defers the introduction of a full capability reusable Tug until the CY 1981-1982 time period.
- A compromise in the capability of the reusable Tug used at IOC of the Space Transportation System could potentially reduce Tug early year funding to around $100 million in the peak year. This reduced capability might take the form of an earth-storable reusable Tug with payload retrieval capability, or a cryogenic reusable Tug without retrieval capability.

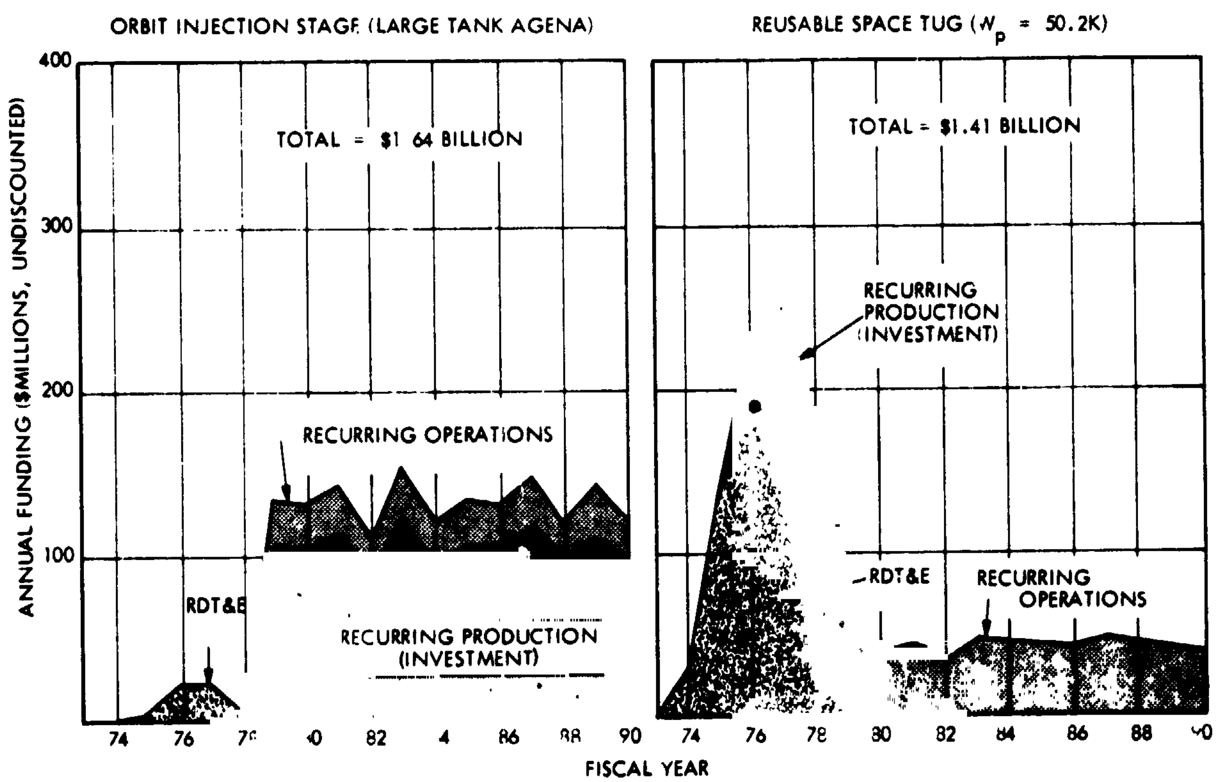


Figure 4-44 Tug Funding Comparison